SUSTAINABLE FOOD: PRODUCTION AND CONSUMPTION PERSPECTIVES

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PREFACE

When looking at the hierarchy of global issues, food production and consumption are among the most significant matters for many reasons.

Firstly, they form the biological basis of the existence of humankind, determining its physical survival. Diet has a huge impact on the health of society, and thus on its many consequences, such as the cost of maintaining the health care system and the cost of social security, to name but a few. The importance of food security and good nutrition for people is so great that its absence can contribute to social and political tensions of enormous magnitude, resulting in such phenomena as wars and migrations.

Secondly, food production and distribution form huge sectors with very numerous and diverse actors. Some of them are characterised by a very high degree of concentration of capital, which can give rise to the risk of oligopolisation of markets on a global scale, with all the negative consequences that this entails in terms of their great economic potential. These include the practice of offering food that is not conducive to health and the difficulty of controlling companies by state authorities, whose annual revenues exceed the annual GDP of many countries in the world.

Food production and consumption have a very strong impact on the degree of sustainability of the economy, both current and future. Food sustainability entails producing food in a manner that safeguards the environment, optimises the utilisation of natural resources, enables farmers to sustain themselves and improves the overall well-being of communities involved in food production, encompassing both people and animals. This concept serves as the impetus for a movement aimed at confronting the reality that our global food system consumes substantially more resources than it generates. According to FAO's report (2022), around 2.3 billion people in the world (29.3% of the global population) were moderately or severely food insecure in 2021: 350 million more compared to before the outbreak of the COVID-19 pandemic. Nearly 924 million people (11.7% of the global population) faced food insecurity at a drastic level, and this number also increased. With the projected global population reaching 10 billion by 2050, there is a necessity for

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a 60 to 70% increase in food production to cater to this additional demand. On the other hand, food production has a very serious impact on the environment. It is estimated that about one third of all greenhouse gas (GHG) emissions may be caused by the global food system. The largest contribution came from agriculture and land use change activities (71%), with the remaining being from supply chain activities: retail, transport, consumption, fuel production, waste management, industrial processes and packaging (Crippa et al., 2021).

Achieving global food security in a sustainable manner is one of the biggest challenges at the present time. It encourages research and popularisation of issues related to both the production and consumption of food in a sustainable way. On the one hand, the scientific topic is the development of technologies and processes that allow the production of food with minimal food losses and minimal negative environmental impact. On the other hand, scientists look for ways to strengthen positive attitudes of food consumers, i.e. shaping the diet in an environmentally friendly way and reducing food losses.

Making food production and consumption sustainable is a challenge that the authors of this monograph would also like to face. The book consists of two parts; the first one is devoted to the issue of food sustainability from the perspective of production, the second one—from the perspective of consumption.

The production perspective part (PART I) starts with a chapter devoted to sustainable food production and processing. The authors present here the main objectives of sustainable production and the European Union plan for sustainable agricultural production, highlighting such concepts as the One Health approach, Climate-Smart Agriculture, European Green Deal and the Farm to Fork Strategy. Additionally, the authors characterise methods applied in food production and processing, based on biological systems, including the use of microorganisms, since they may diminish the adverse environmental impact of modern food production. The authors of the second chapter focus on a broader perspective of sustainable farming, including both economic, environmental and social dimensions. The objective of this chapter is to assess the interaction between these dimensions of agricultural activity and to identify cause-and-effect relationships between them, using the example of family farms in Wielkopolska, i.e. one of the regions in Poland. The authors indicate the need to always consider agriculture as a broad and complex economic, social and environmental system, and to adjust the policies according to the region's peculiarities with its unique features. The third chapter brings a different perspective on food production, as it is devoted to digitalisation in the agri-food sector, which should be recognised as a set of modern solutions supporting and facilitating sustainability in food production. Industry 4.0 technologies are increasingly used in food production, leading to the development of Agri-Food 4.0. The use of the Internet of Things, artificial intelligence, big data and cloud computing enables advanced planning, control and optimisation of food production both in agriculture and food processing. It positively affects the quality and safety of food and has a positive impact on the efficiency of the food chain process. The fourth chapter generally presents a modern approach to the packaging design that supports food sustainability. Concern for environmentally friendly packaging and packaging materials facilitates the development of its design in terms of recycling and increasing popularity of reusable packaging. Food sustainability is also one of the main prerequisites in the packaging optimum approach and ensuring product accessibility via its packaging applied in the supply chain. Active packaging systems allow producers to extend the shelf life of food, and intelligent packaging supports the reduction of food waste and losses. Modern solutions for automatic data collection, such as RFID tags and geolocation systems, can also support the management of data on food products in logistics. The fifth chapter highlights the circular economy perspective in food production and processing sectors. It summarises the life cycle-based tools that have potential for complimenting the implementation of circular economy in the food system. Based on that, the study identifies the current challenges as well as the benefits and potential of life cycle-based tools for providing a holistic approach that could strengthen available circular economy solutions. The last chapter within the first part contains a review of sustainable strategies presented in the literature for managing fruit processing by-products according to the circular economy principles. Sustainable management of fruit processing by-products is important to reduce the amount of food waste deposited in landfills and to develop strategies through their reuse for full valorisation and economic value added.

The second part of the monograph (PART II) is oriented on the consumers' perspective. The seventh chapter included in this part presents the concept of a 'sustainable healthy diet' in the context of international and national dietary guidelines, as well as the environmental impact of production and consumption of selected food groups and types of dietary patterns. The authors of the eighth chapter provide an overview of the assortment, market and consumption of various meat alternatives. Products replacing meat are made of various types of (mostly) plant-based raw materials including pulses/legumes, cereal proteins (mainly gluten), oilseeds, fungi (edible mushrooms) and algae; however, cultured meat and edible insects are also described. The ninth chapter is devoted to the food labelling system presented from the consumer's perspective. The aim of this chapter is to discuss the latest research showing how food labelling can support consumers in their healthy and sustainable purchasing decisions. It presents both front-of-pack (FOP) nutrition labelling and its influence on consumers' perception of product healthfulness and purchase intention, as well as date labelling and its consequences. The tenth chapter is dedicated to the sustainable food consumption manner. The authors report the results of a bibliometric literature review conducted to explore the current state of research on shaping sustainable food consumption attitudes.

The aim of the eleventh chapter is to identify the causes of food waste generated by households. To achieve their aim, the authors adopted a conceptual framework based on the assumption that household food waste originates in three predictable stages—shopping, storing and serving. The work presents the level and structure of food waste by food category, continents, and countries. Finally, the objective of the last chapter is to present solutions designed to redistribute surplus food as a food waste prevention tool. Surpluses of food are generated both in supply chains and in households. This chapter presents the structure of the surplus food redistribution system (SFRS) in terms of entities included in it. Three main types of SFRS institutions are presented here: food banks operating both as front-line and warehouse entities, social supermarkets and sharing systems, which work as initiatives based on some premises (physical places) where food may be left and taken from, as well as operating thanks to Internet platforms.

Our objective, as the editors and authors, is to disseminate widely the concept of food sustainability among both scientists and researchers, as well as among practitioners directly and indirectly related to food production and consumption. We truly hope that this monograph will help to make processes related to food more sustainable—at least a bit.

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PART I
SUSTAINABLE PRODUCTION

1. SUSTAINABLE FOOD PRODUCTION AND PROCESSING—SUSTAINABLE AGRICULTURE AND BIOTECHNOLOGICAL APPROACHES IN FOOD CHAIN

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Abstract

The current trend of the increasing human population as well as the evolution of consumption patterns, increasing food demand and growing amounts of food waste influence changes along the entire food chain, from agricultural systems and natural resources to processing. It is worth underlining that the agri-food industry is considered one of the most important sectors of economic development in the world. However, the increased demand for food is depleting natural resources, causing soil erosion, landscape biodiversity loss and environmental pollution worldwide, creating new challenges for food security and sustainable food production. Therefore, sustainable agriculture and new technologies and approaches play an increasingly significant role in reducing negative environmental impacts while ensuring food safety. It stays in line with the model of food production development promoted by the Food and Agriculture Organization of the United Nations, according to which sustainable agriculture means the production of healthy, high-quality food in an environmentally friendly way, caring for animal welfare and protecting biodiversity, as well as ensuring income for farmers. This approach is also consistent with many concepts focused on the issue of sustainable, eco-friendly food production, such as development of sustainable agriculture, the One Health concept, Climate-Smart Agriculture, the European Green Deal and the Farm to Fork Strategy, strongly emphasising efforts to create a healthier and more sustainable food system.

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JEL codes: O13, Q01, Q16, Q57.

Introduction

As the literature data underline, the global human population is expected to reach 9.7 billion people by the year 2050 (United Nations Department of Economic and Social Affairs, 2015), which means that food production will need to increase. This puts a heavy burden on agriculture and its related sectors to meet the demand for food. Furthermore, the Food and Agriculture Organizations (FAO) report entitled *The future of food and agriculture: Trends and challenges* identifies some requirements ensuring adequate as well as affordable food supplies through sustainable agriculture in order to meet the increasing demand of the growing population. This report draws attention to the current and most urgent trends emphasising the complexity of agriculture and the food supply system as well as the opportunities and challenges necessary for its sustainability. In turn, the key challenges that food and agricultural systems will face in the nearest future can be divided into three groups: challenges for food stability and availability (including sustainable improvement of agricultural productivity with providing a sustainable natural resource base and taking into account climate change), challenges for food access and utilisation (including eradication of extreme poverty and reduction of inequalities, fight against hunger and malnutrition as well as drawing attention to the improvement of earning opportunities in rural areas, reasons for migration, crises, disasters and conflicts) and systemic challenges (with paying attention to food systems and effective governance at national and international levels (FAO, 2017). It is also worth quoting an important document indicating the goals facing today's societies entitled „Transforming our world: The 2030 Agenda for sustainable development", signed in 2015 by the leaders of the United Nations (UN) (UN, 2015). Among the 17 Sustainable Development Goals (SDGs) and the related 169 targets, which are to be achieved globally by 2030, SDG 2 underlines the necessity of more productive and less wasteful agriculture systems. In order to achieve this goal, a major transformation is needed in terms of what food is consumed and how it is produced, processed, transported and distributed. Therefore, the role of sustainable agriculture and new technologies and approaches will be of particular importance in reducing negative environmental impacts while ensuring food safety. It is consistent with the model of development of food production promoted by the FAO, according to which sustainable agriculture means the environmentally friendly production of healthy, high-quality food with care for animal welfare and biodiversity protection, as well as ensuring income for farmers.

Other concepts, such as the One Health approach, Climate-Smart Agriculture (CSA) or European Green Deal (EGD) and the Farm-to-Fork (F2F) Strategy, also stay in line with the above-mentioned FAO model. The idea of the One Health concept, established in 2004, assumes a strong connection between the health of people, animals and the environment. This approach involves multidisciplinary teams from different institutions working together to increase sustainable agriculture practice and improve health, society and conservation of natural resources while building social awareness. The One Health approach has been supported by organisations such as the World Health Organization (WHO), the FAO, the United States Centers for Disease Control (CDC) and the European Joint Program One Health (OHEJP) (FAO, 2010, 2013). In turn, CSA, according to the FAO, is a strategy that pays special attention to climate change, sustainably increases productivity, increases resilience through adaptation to climate change and reduces greenhouse gas emissions (FAO, 2010). As shown in Figure 1.1, sustainability is based on the link between the society (people), environment (planet) and economic value (profit), and an important challenge for public and private policy is to take them into account all together.

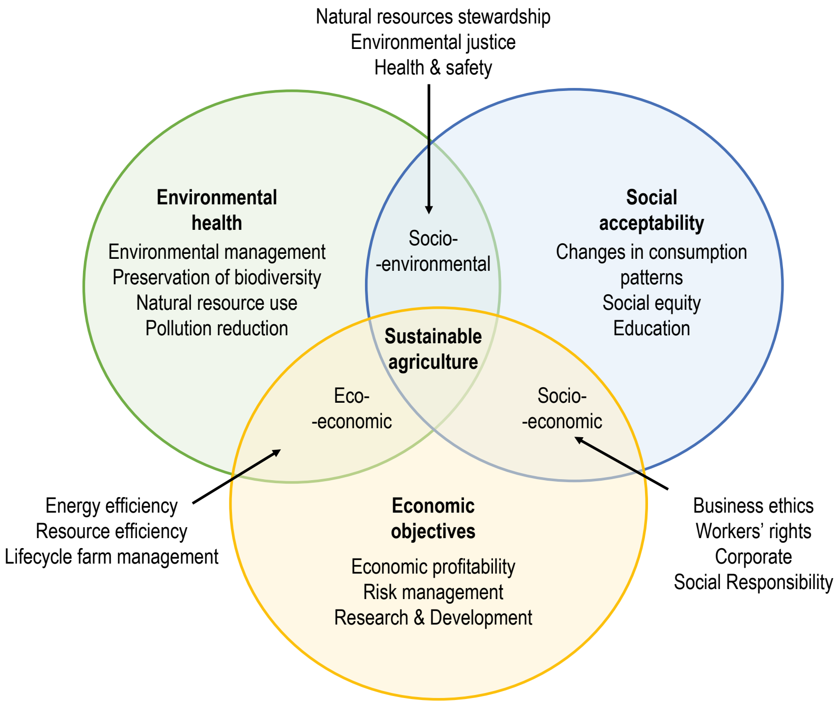

Figure 1.1. Venn diagram showing the relationship between three main objectives of sustainable agriculture

Source: based on (Abubakar & Attanda, 2013; Clark et al., 2021; Fenibo et al., 2022).

This direction of agricultural development and its transformation is to ensure food security and sustainable development of agriculture around the world, including poor countries. It should be emphasised that agriculture is the dominant economic direction in many countries and is crucial for meeting the basic needs and livelihoods of 70% of the world's poorest people (Global Commission on the Economy and Climate, 2014). Thus, adaptation, mitigation and food security as the three pillars of CSA will have significant implications for the world's poorest farmers. In Europe, the consequences of climate change and environmental degradation, already visible and possible in the future, have provided the basis for the development of an action plan called the EGD. Referring to the above-mentioned concepts and assumptions introduced in Europe and around the world, it may be said that all of them are perceived as caring for the environment and human well-being, with the common goal being sustainable development. In relation to sustainable food production and processing, it needs to be highlighted that sustainable food can only be obtained when the production process is environmentally and climate-friendly, economically justified and socially accepted. This concept is strongly related to the sustainable agriculture model, in which the negative impact of agricultural production on the environment is limited and available resources are used more efficiently. In this context, sustainable agriculture includes many elements, starting with the farmers' selection of practices, methods and tools for cultivation or breeding, usage of water, energy, machinery, plant protection products and fertilisers or seeds to caring for animal welfare, preservation of biodiversity around the farm, usage of methods which do not degrade soil, efficient water management and reduction of greenhouse gas emissions. Throughout the process, it is important that the choices made do not raise social objections.

1.1. European Union plan for sustainable agricultural production

The most important drivers of sustainable development, undoubtedly, include agricultural production. Unfortunately, as a key element in ensuring adequate food resources for a growing population, it can also be a significant obstacle to achieving the SDGs (Melchior & Newig, 2021). The intensification of production in the agricultural sector is often associated with the use of unsustainable agricultural practices, which in turn leads, among others, to the degradation of forest areas, increased greenhouse gas emissions, reduction of biodiversity or degradation of soil and water resources (Ramankutty et al., 2018). To reduce the negative impact of agriculture on the environment and natural resources, various models of agricultural production have been developed over the years, such as agri-environmental, integrated farming system (IFS), Low-Input Sustainable Agriculture Program

(LISA) as well as alternative agriculture involving systems such as organic, biodynamic, low external input or resource-conserving and regenerative (Bowler, 2002). Furthermore, it should be stated that in addition to counteracting negative environmental impacts, sustainable agriculture must simultaneously consider appropriate economic and social development. Accordingly, all over the world, various practices and regulations are being adopted to steer agricultural production along the path of sustainable development (FAO & UNEP, 2020).

European agricultural policy for obtaining sustainability has evolved progressively, adapting its assumptions to the economic socio-environmental situations in which it was operating at the time (Wrzaszcz, 2023). The first steps of agricultural improvement in the European Union (EU) date back to the 1960s, when the principles of the Common Agricultural Policy (CAP) were introduced. The CAP established economic and social objectives such as: (1) increasing agricultural productivity by promoting technical progress and optimal use of factors of production, especially labour; (2) ensuring a decent standard of living for farmers; (3) stabilising markets; (4) guaranteeing the security of supply and (5) ensuring reasonable prices for consumers, which, by their nature, were easily adaptable to subsequent reforms (Nègre, 2023). However, it should be noted that at the beginning the CAP was implemented through agricultural intensification (maximisation of production), the policy of guaranteed prices and unlimited purchase warrants leading to a lot of environmental damage or increasing surplus production (Nègre, 2023; Włodarczyk, 2022). Significant changes in the CAP took place in the 1990s due to the MacScharry reform,[1] which linked agricultural activities with environmental aspects, introducing, among others, measures to stimulate the use of environmentally friendly methods, including those aimed at intensifying agriculture and strengthening the importance of agricultural activity in environmental protection in rural areas (Wrzaszcz, 2023). The new look at agricultural production was reflected in later reforms, such as Agenda 2000 (protecting ecosystems and ensuring animal welfare), the 2003 Luxembourg reform (ensuring an appropriate level of agricultural income—1st pillar of the CAP, and supporting the development of rural areas and protection of the natural environment—2nd pillar of the CAP) and the 2013 reform (main issues of the reform: rural development; direct payments to farmers and market cooperation; management, financing and monitoring of the CAP), putting the CAP on a sustainable path by taking into account the productive, social and environmental aspects of agriculture (Adamowicz, 2021). Currently, all

[1] MacSharry reform, developed in 1992 by Ray MacSharry, European Commissioner for Agriculture and Rural Development (1989–1993), the first large-scale reform of the CAP, aiming at reducing the overall budget and quitting unlimited guaranteed prices. Finally, the policy contributed to direct income support for farmers, who were obliged to safeguard the environment, and incentives to improve food quality (European Council, n.d.; Historical Archives of the European Union, n.d.).

reforms and actions for sustainable agriculture are based on the EGD–a strategy that, as the European Commission (2019) stated, aims to:

> transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use (…), protect, conserve and enhance the EU's natural capital, and protect the health and well-being of citizens from environment-related risks and impacts.

The EGD puts agricultural production in a key position in the proper course of transformation and achievement of the assumed ambitious goals. The main objective of the EGD strategy is to put sustainable development and human well-being at the heart of economic policy, involving all stakeholders from various sectors, such as construction, biodiversity, energy, transport, agriculture and food. In the case of agriculture and food, the policy based on the F2F Strategy assumes:

- ensuring sustainable food production and promoting sustainable practices throughout the food industry,
- ensuring food security,
- promoting sustainable consumption and reducing food loss and waste,
- combating food fraud in the supply chain (EC, 2019).

The F2F Strategy is an important document aimed at building a sustainable food system; nevertheless, agriculture also plays a role in other economic assumptions, such as "climate neutrality" or the circular economy (Adamowicz, 2021). In the adopted strategy, agricultural production will play a significant role in sustainable production through activities including in particular:

- introducing agricultural practices that reduce emissions of CO_2 and other greenhouse gases (through changes in animal husbandry),
- increasing the use and development of energy production from renewable sources and investing in digesters,
- reducing the use of chemical plant protection products,
- reducing the use of antimicrobials in animal husbandry,
- improving animal welfare to ensure safe and high-quality food,
- reducing excess nutrients (especially nitrogen and phosphorus) in the environment,
- increasing the importance of an organic farm in agricultural production (strictly regulated and controlled under Regulation (EU) 2018/848 with subsequent amendments),
- increasing the financial support (eco-schemes) of sustainable agricultural practices such as precision farming or agroecology (including organic farming) (EC, 2020).

Furthermore, important support and, at the same time, a key tool for the implementation of the developed concepts of sustainable agriculture is the new CAP 2023-27. The new approach to the CAP allows for greater flexibility and takes into account local needs and conditions. The key document is Regulation (EU) 2021/2115, which defines the general objectives and 10 specific objectives, which are largely convergent with the assumptions of the EGD and the F2F Strategy or actions for biodiversity. The document also defines detailed rules for financial support for the agricultural sector, including in particular the European Agricultural Guarantee Fund (EAGF) and the European Agricultural Fund for Rural Development (EAFRD). Another important provision is related to strategic plans, which are developed individually by each member state and are assessed and monitored by the European Commission (Regulation (EU) 2021/2115, 2021). Thus, it can be seen that the implemented reform will, in fact, move away from its normative nature, focusing on results (in particular, the environmental ones) and increasing the role of Member States in the whole process (Leśkiewicz, 2020).

It is apparent that the plans introduced by the EU for sustainable development of agriculture are wide-ranging and very ambitious. Nonetheless, it should be noted that achieving appropriate economic results in agricultural production (economic aspect), ensuring the development of rural areas or adequate quantity, good quality and safe food (social aspect), while minimising interference with the environment and acting for its protection (environmental aspect) is a multi-dimensional, complicated process depending on many factors. In order to achieve the assumed goals and properly transition to a more sustainable model, further work is necessary on appropriate regulatory, financial and advisory support for the agricultural production sector, which is another major challenge for the EU.

1.2. Integrated agricultural systems

Meeting the growing demand for food in a sustainable way requires a shift from industrial agriculture, which is primarily focused on production, high productivity, self-sufficiency and affordability (Prost et al., 2017) to sustainable agriculture, which is environmentally friendly, socially acceptable and economically viable. Many alternative forms of agriculture have emerged in the meantime, such as permaculture, biodynamic agriculture, organic farming, natural farming, aquaponics, vertical farming, urban farming, precision farming, social and welfare farming, agroecology and "smart" or digital farming (Hassink et al., 2018; Ingram, 2018; Junge et al., 2017; Wezel et al., 2009; Wolfert et al., 2017); moreover, bioeconomy and circular economy have also developed (Borrello et al., 2016). However, it should be underlined that there are a number of threats present in agricultural production that negatively affect crops, such as plant diseases or droughts, which forces farmers to use solutions preventing losses and lowering the quality of crops. Various types of fertilisers, growth stimulants and pesticides are used on a large scale, which increases production on the one hand, but also affects the environment on the other hand. Therefore, methods based on biological systems, including the use of microorganisms, are of increasing interest since they may diminish adverse environmental consequences of modern agricultural production.

Beneficial microorganisms can increase yields by stimulating plant growth, removing pollutants and inhibiting the development of pathogens. Their properties are used in biofertilisers and biopesticides, designed based on different microorganisms. Biofertilisers are bio-based organic fertilisers that could come either from plant or animal sources, defined as preparations containing live microorganisms that help to increase soil fertility through various mechanisms, including fixing atmospheric nitrogen, dissolving phosphorus, decomposing organic waste, as well as enhancing plant growth through the production of growth hormones (Okur, 2018). Taking into account the origin and type of the raw material, we distinguish biofertilisers based on organic residues (green manure, crop residues, treated sewage sludge and manure) and biofertilisers based on microorganisms (containing beneficial microorganisms such as bacteria, fungi and algae) (Abbey et al., 2019; Lee et al., 2018). Stimulation of plant growth by microorganisms may result from different mechanisms, such as biological nitrogen fixation, phosphate solubilisation, micronutrient solubilisation, production of growth regulators, such as IAA (indole-3-acetic acid), gibberellic acids and cytokines, as well as increasing the bioavailability of minerals (Chaudhary et al., 2021). Moreover, some indirect mechanisms, such as releasing lytic enzymes, antibiotics, siderophores and cyanide production by microorganisms, may also be responsible for protecting the plant from pathogens (Mahmud et al., 2021). The advantages of biofertilisers, in addition to the basic properties, such as increased availability of nutrients and improvement of soil fertility, also include benefits such as low cost, protection of plants against soil-borne pathogens and increased tolerance to biotic and abiotic stress. It is also worth noting that the use of biofertilisers is associated with less environmental pollution while maintaining soil biodiversity, which contributes to sustainable agricultural production (Chaudhary et al., 2022).

The second group of products of significant importance for sustainable agriculture are biopesticides based on living organisms or natural products, demonstrating antimicrobial or insecticidal activity (Glare et al., 2012; Thakore, 2006). According to the United States Environmental Protection Agency (EPA, 2023), these compounds are "derived from natural materials such as animals, plants, bacteria and certain minerals". Biopesticides as an ecological alternative to traditional agricultural technology are a crucial component of integrated pest management programs. Depending on the type of compounds, different categories can be distinguished, such as microbial pesticides, biochemicals and plant-incorporated protectants.

Microbial pesticides are derived from different microorganisms including bacteria, fungi or viruses demonstrating activity towards pathogenic bacteria, fungi or insects. Their activity is often related to the production of different metabolites. The most frequently mentioned bacteria used as biopesticides are species of *Bacillus*, *Pseudomonas*, *Yersinia*, *Chromobacterium*, *Serratia*, and *Streptomyces*, while fungi include species of *Beauveria*, *Isaria*, *Metarhizium*, *Verticillium*, *Lecanicillium*, *Hirsutella* or *Paecilomyces* (Chang et al., 2003; Ranga Rao et al., 2007; Thakur et al., 2020). An important group of microbial pesticides are baculoviruses active against chewing and biting insects, such as *Lepidopteran caterpillars*. Insecticidal nematodes (EPNs) used as biocontrol agents are mainly species of the genera *Heterorhabditis* and *Steinernema* associated with the symbiotic bacteria of the genera *Photorhabdus* and *Xenorhabdus* (Chang et al., 2003).

Biochemical biopesticides are compounds of natural origin demonstrating activity towards pests by nontoxic mechanisms such as extracts or essential oils obtained from different plants, semiochemicals, plant growth-promoting regulators or insect pheromones (Kumar, 2012; Reddy & Chowdary, 2021; Singh et al., 2021). The compounds responsible for the insecticidal activity include phenolics, steroids, alkaloids, terpenoids, phenylpropanoids and nitrogenated compounds (Duan et al., 2016; Weber et al., 2019).

The third group of biopesticides are plant-incorporated protectants (PIPs), which are substances produced by genetically modified organisms (GMOs). The incorporation of genetic material into plants renders them unsuitable for pest attack. The best-known insecticidal molecules used in PIP technology are Cry proteins from the soil species of *Bacillus thuringiensis*, protease from Baculovirus, toxic complex (Tc) proteins from bacteria of the genera *Xenorhabdus* and *Photorhabdus*, as well as double-stranded ribonucleic acid (dsRNA) and Mir1-CP from maize (Fenibo et al., 2021; Parker & Sander, 2017; Shingote et al., 2013; Wei et al., 2018).

Biofertilisers and biopesticides play an important role in integrated agriculture systems as these solutions are environmentally friendly, may support the preservation of biodiversity and are less harmful to humans and animals.

1.3. Biotechnological applications for sustainable food production and processing

To ensure sustainable food production and processing, improving the effectiveness and efficiency of food systems is urgently required nowadays. In recent years, there has been a clear impact of biotechnology on industry and agriculture, e.g., by improving the quantity and quality of products. In the agricultural sector, biotechnological solutions play a significant role, ranging from increasing the efficiency of crops or animal husbandry to improving agricultural products, while ensuring that their environmental impact is reduced. Therefore, recent developments in agricultural biotechnology significantly support the food sector, ensuring its global security (Figure 1.2). The biotechnological achievements concern both the solutions introduced in the field as well as at further stages of the food chain. In addition to the above-mentioned solutions, which use biological systems, agriculture is increasingly reaching for solutions based on "omics" technologies and genetic modifications. For example, new plant breeding techniques (NPBTs) based on genome editing are promising technology employed in the food and agriculture industries for a variety of purposes, including genetic improvement of plant varieties and animal populations, characterisation and conservation of genetic resources and other uses (Tyczewska, Woźniak et al., 2018).

The genetic modifications of plants may improve their tolerance to environmental stress, such as drought, or introduce resistance to any diseases or pests. Moreover, some features crucial in food processing, such as increased purity or high yield efficiency, as well as features important from a nutritional point of view, may be improved by new biotechnological techniques. Interestingly, engineering plants can have a positive effect on the environment as they may efficiently absorb soil nutrients and reduce the use of agrochemicals, in turn reducing environmental pollution (Barrows et al., 2014; Ranjha et al., 2022; Tyczewska, Twardowski et al., 2023; Zhang et al., 2016).

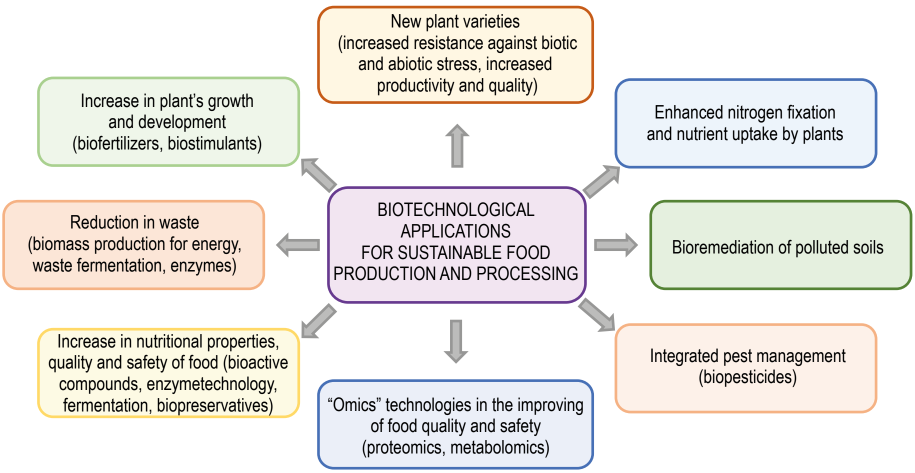

Figure 1.2. Biotechnological applications for sustainable food production and processing

Source: based on (Gosal et al., 2020; Lokko et al., 2018; Tyczewska, Twardowski et al., 2023).

Industrial biotechnology, in turn, plays a significant role in food production and processing, providing products that fit into new production and consumption patterns.

The solutions used in this field include fermentation, enzymatic biocatalysis, and even gene technology. Fermentation is one of the oldest known biotechnological processes and a key component of many industrial applications to obtain many different products, giving great opportunities for their modification and improvement. Similarly, enzyme biocatalysis has wide industrial applications including food and feed production (Lokko et al., 2018). Furthermore, the biotechnological use of microorganisms and their metabolites plays an important role at all stages of the food chain, being part of biopreparations used in agricultural production, taking part in the processes of degradation and biotransformation of waste and pollution, as well as in the processing of food or feed. It should also be emphasised that the "omics" technologies (genomics, transcriptomics, proteomics, metabolomics) used for the development of agricultural biotechnology, bioproducts and food biotechnology, are becoming increasingly important (Amer & Baidoo, 2021).

Conclusions

Agriculture is an important sector of the economy in many countries. However, conventional agriculture, which uses chemical fertilisers and pesticides to increase yields and production, negatively affects the ecological balance and food security, and is a major contributor to land and water pollution. Therefore, the idea of sustainable agriculture is becoming more and more important (Raman et al., 2022). Implementation of the assumptions for sustainable food production and processing requires multi-directional activities, in which biological systems and achievements of biotechnology have a significant share. Biotechnological innovations offer solutions to various civilisation challenges faced by today's world, including broadly understood sustainable agriculture, from improving crops through reducing waste from the agri-food industry to improving food. Biotechnological solutions can contribute to sustainable development by helping to achieve the SDGs, in particular, Goal 2—aiming to end hunger and achieve food security; Goal 9—emphasising the promotion of inclusive and sustainable industrialisation and supporting innovation, and Goal 12—indicating the need to ensure sustainable consumption and production patterns.

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2. FARMING SUSTAINABILITY—INTERACTIONS OF ECONOMIC, ENVIRONMENTAL AND SOCIAL DIMENSIONS

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Abstract

The conviction that farm development depends not only on the economic dimension but also on the environment as well as the social dimension, is increasingly widespread. The purpose of this study was to assess the interaction between the economic, social and environmental fields of agricultural activity and to identify cause-and-effect relationships between the aforementioned dimensions on the basis of family farms in Wielkopolska. The study was based on a literature review and the results of surveys conducted among 120 farms in the Wielkopolska region of Poland. Having applied structural equation modelling analysis, the authors discovered that there are significant mutual positive relations between the economic, social and environmental spheres in the analysed farms. Thus, those relationships can be complementary to each other. The presented research indicates the need to always consider agriculture as a broad and complex economic, social and environmental system, as the European Union already does, and to adjust policies according to the region's peculiarities and its unique features. Simultaneously, one should aim to achieve multiple and diversified goals in agriculture.

Keywords: sustainability, farming, European Union, environment, low carbon.

JEL codes: Q01, Q12, Q56.

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Introduction

As the issues related to sustainability are more and more relevant in everyday life, they resonate particularly strongly in modern economics. The already theoretically established paradigm of sustainable development (Czyżewski & Kułyk, 2013; Zegar, 2007, 2018), placed between mainstream and heterodox economics, which assumes the dynamic achievement of harmony between economic, social and environmental dimensions—as practice shows—is not easy to achieve at different levels. The pursuit of sustainability reveals the need to take into account in economic studies full external costs and benefits, including the environmental ones, towards the compatibility of the microeconomic and social optimum. Thus, it is problematic to reconcile microeconomic efficiency, aimed primarily at satisfying the needs of the individual, with macroeconomic rationality, where community-wide, national interests are more important (Kulawik, 2007; Van Huylenbroeck et al., 2004). It is troublesome to raise economic efficiency, where economic results are the key, while achieving social equity, where the individual is the focus (Krasowicz, 2009; Krysztofiak & Pawlak, 2017; Pimentel, 2006; Tarnowska, 2010). At the same time, these socio-economic processes are embedded in the environment, with which there is a feedback loop usually manifested in negative environmental externalities.

These phenomena also relate to the agricultural sector, where there are interactions between the aforementioned areas, i.e. economic, social and environmental. In the light of the paradigm of sustainable development, it is desirable to harmoniously achieve the three key dimensions, but the practice embedded in the industrial, microeconomic, purely market-based approach indicates that in economic activity, economic issues most often take the lead, with social issues receding into the background, and the greatest cost is borne by the environment. However, modern economics sees an increasing need to integrate the aforementioned areas and strengthen positive interactions between them, because there is a conviction that the final, broad profit and loss account that internalises social and environmental issues will prove more beneficial in the long run.

Thus, the purpose of the study was to assess the interaction between the economic, social and environmental dimensions of agricultural activity and to identify cause-and-effect relationships between the aforementioned orders, using the example of family farms in Wielkopolska. Despite the above-mentioned difficulties associated with the effort to make farms sustainable, we want to show that it is possible to simultaneously achieve the economic and social order, together with the environmental order.

2.1. Literature review

The agricultural sector faces a number of problems, with increasing requirements being placed on farmers. They should produce while respecting soil, water resources, the atmosphere and biodiversity (Kleijn et al., 2009; Matson et al., 1997; Tilman et al., 2001; Tscharntke et al., 2005), and at the same time, their activities should be profitable so that the farmer's family may live with dignity and the farm can develop. Moreover, food security in terms of physical and economic availability of food and its quality also largely depends on them. It should be noted, however, that it is difficult to reconcile the provision of food security and income for food producers with the preservation of the natural environment, where constraints, resulting from this environment, force the restoration of disturbed equilibriums so that agriculture, or existence, can continue (Matuszczak, 2020). The symptoms of disharmony in the economic, social and environmental order in agriculture are manifold, including the inability of agricultural income to keep up with increases in agricultural labour productivity (efficiency) and increasing pressure to create public goods in rural areas threatened by environmental and climate destruction. One of the reasons for this is the mechanism of technological treadmill, which forces further industrial development of agriculture (Chen et al., 2011; Czyżewski, 2017; Levins & Cochrane, 1996). Under these conditions, while agricultural income is growing, it does not keep up with the growth of income in non-agricultural sectors. This income disparity is accompanied by social deprivation of farmers. As a result, agricultural production structures are changing, but some space for environmental action is also created. This is because the need for the supply of environmental public goods emerges (OECD, 2015; Viaggi et al., 2021; Villanueva et al., 2014; Westhoek et al., 2013). Thus, the rationale for clarification and implementation of a model of sustainable development of agriculture arises. Under these conditions, it becomes necessary to strive for sustainable development of farms, where, on the one hand, care is taken to pay for the involvement of their own productive factors (labour, land and capital) in the operational activities of the farm and payment for the risks taken by the farmer, i.e. *de facto* income, including education, and on the other hand, the inputs that constitute the factors creating environmental pressure in agricultural activities are monitored so that the relationship can be maximised.

In the literature, we can find positive examples indicating that family farming makes an important contribution to the sustainability of the sector, as there are positive interactions between the socio-economic aspects, while at the same time being more concerned about the use of natural resources and focusing on practices that respect the environment (Bosc et al., 2013; Piedra-Muñoz et al., 2016). Family farms "are the best hope for a sustainable future for agriculture and for humanity," but this requires achieving harmony between the environmental, social and economic perspectives of sustainability (Ikerd, 2013; Pretty, 2008; Saifi & Drake, 2008; United Nations, 2015).

However, despite the consensus that it should be harmonious to achieve the three orders, it is not common to analyse the interactions between them. An attempt to do so can be found in the work of Rajaram and Das (2010) who suggested using a "fuzzy rule approach" to model the interactions of sustainability components in an agroecosystem. The need to analyse the relationships between the dimensions of sustainability was also pointed out by the European Commission (2001). Interdependencies and interactions between the different orders were pointed out by Galdeano-Gómez et al. (2012, 2017), who used the example of the Almeria region (Spain), as well as between the social and economic dimensions in that region presented by Torres et al. (2016). Other studies point to the links between sustainability (understood in terms of socio-economic characteristics, environmentally friendly practices and innovation) and profitability, indicating that harmonised elements of sustainability promote higher farm profitability (Piedra-Muñoz et al., 2016).

This research contributes to the above-mentioned discussion by showing the relationship between the environmental, economic and social dimensions of agricultural activity, on the example of farms from Wielkopolska. In this work, low carbon is a development (deepening) of the environmental dimension due to the increasing importance of climate issues within the environment. Examples of research results (Li et al., 2016) suggest that decreasing energy intensity in agriculture is the main factor behind declines in CO_2 emissions, and increasing energy efficiency is a more effective mean to reduce CO_2 emissions than changes in the fuel-mix. Furthermore, France, Finland, Sweden, Denmark, the Netherlands, Poland and Belgium have the highest potential for reduction in CO_2 emissions in agriculture.

2.2. Material and methods

To analyse various interactions between farming dimensions we used structural equation modelling (SEM). This advanced technique is considered to be a very good and effective way for analysing interdisciplinary issues within sustainable development or environmental economics (Brown, 2015; Hooper et al., 2008). Therefore, it could be employed in our project where we discovered relationships between economic, social and environmental fields of farming. Modelling of structural equation allows us to combine the advantages of analysis of variance, regression and factor analysis, extending them with the possibility of modelling cause-and-effect relationships using latent variables (Garson, 2015; OECD, 2008). In our study, latent variables are economic, social and environmental performances of farms. While using SEM, we can identify indirect, direct and total independencies between variables—both latent (construct) and observed variables (Garson, 2015; Anghel et al., 2019). A huge advantage of SEM is the possibility to add relationships between different variables, which allows us to make to model more complex systems of interactions between variables. Broad descriptions of SEM, with its many different types and advantages, are presented by Garson (2015), Hoyle (2012) and StataCorp (2017).

In the presented research, the results of a survey conducted in 2020, focusing on 120 agricultural holdings from the Wielkopolska region were used. These holdings are part of the farm accountancy data network (FADN). The holdings were divided proportionally based on both the type of farming (TF) and the economic size of the farms (ES). The selection of units for the study was purposive-random, aiming to capture a diverse range of participants. An interview questionnaire titled "Assets and income in agricultural holdings in the paradigm of sustainable development" was used as a research tool (Grzelak, 2019). The interviewers assigned to the selected farms were advisors from the Agricultural Advisory Centre, contributing to the collection of highly reliable research material. Throughout the survey, only in a few instances (nine cases), was there a need for the questionnaires to be supplemented with explanations from the interviewers. This occurred particularly in situations involving outlier observations, where additional information was required.

2.3. Results and discussion[1]

During the analysis of the data, multiple models were developed to explore the interactions between economic, social and environmental variables related to family farms in the Wielkopolska region of Poland. Structural equation modelling was used to analyse the data. The most favourable model, as illustrated in Table 2.1, was selected for presentation. As depicted, each latent variable representing the three dimensions of sustainability was constructed using a set of original variables. In the economic pillar, we included positive determinants such as agricultural output, agricultural income and land value, while the negative indicator was represented by the sale of products from the farm without any contracts (*ad hoc*). Regarding the environmental dimension, the positive factors consisted of maintaining grassland on the farm and implementing a fertiliser plan, while the negative influence was associated with a high proportion of cereals in the crop structure. Within the social domain, the positive drivers were a significant share of agricultural income in the household's total income and having agricultural education, while the negative

[1] Collecting data for the research was financed by the National Science Centre in Poland (grant no. 2018/29/B/HS4/01844).

determinant was a high percentage of expenditure on food in the household's total expenditure. This comprehensive model provides a holistic understanding of the integration among the analysed farms, showcasing their ability to excel simultaneously in economic, social and environmental aspects. Consequently, no conflicts arise, such as those between economic and environmental activities or between economic and social performance, within the investigated Polish farms.

Table 2.1. Dimensions of farming within the sustainability concept and their determinants in family farms from the Wielkopolska region, Poland

Economic (latent variable)	**Environmental (latent variable)**	**Social (latent variable)**
x_1: Value of agricultural output given in EUR	x_5: The area of grassland in hectares	x_8: Share of agricultural income in the household's total income (0–100%)
x_2: Land value given in thousands EUR	x_6: Does the farm have a fertilising plan (1 = yes; 0 = no)?	x_9: Type of education (1 = agricultural education; 0 = non-agricultural education)
x_3: Agricultural income given in thousands EUR	x_7: Share of cereals in the structure of crops (0–100%)	x_{10}: Share of expenditure on food in the household's total expenditure (1 = below 10%; 2 = 10–20%; 3 = 20–35%; 4 = 35% and more)
x_4: Type of integration with the market (1 = sale of products without contracts, *ad hoc*; 0 = other)		
Main interactions (max. 1): Economic & environmental: positive (0.54) Economic & social: positive (0.44) Environmental & social: positive (0.35)		
Additional interactions (max. 1): Land value & grassland: negative (–0.29) Land value & food expenditure: negative (–0.18) No contract & food expenditure: positive (0.21)		

Source: based on (Grzelak et al., 2022).

The positive relationships between economic, environmental and social dimensions among farms were confirmed, among others, by Gómez-Limon and Sanchez-Fernandez (2010), Galdeano-Gomez et al. (2017), Haileslassie et al. (2016), Sulewski and Kłoczko-Gajewska (2018). The most common positive interactions seem to occur between the social and economic dimensions; however, the economic-environmental link is gaining more and more importance both at the farm and agricultural sector levels, which is the case due to several facts. In brief, the good environmental condition is necessary for the long-term economic viability.

There is growing concern among farmers and consumers about the state of the environment. Policies (agricultural, climate and energy) require better matching of economic activities to environmental limitations. For this reason, the authors explored the economic and environmental link deeper and in a more detailed form, which made it possible to identify the drivers of low-carbon agriculture among farms in the Wielkopolska region (Table 2.2). Additionally, we aimed to define low-carbon agriculture as a concept and part of a broader idea of a low-carbon economy.

Table 2.2. Low-carbon agriculture and its drivers in family farms from the Wielkopolska region, Poland

<table>
<tr><th>Low-carbon agriculture (latent variable)</th><th>Productivity (latent variable)</th></tr>
<tr><td>Fertiliser use efficiency (the ratio of agricultural output in thou. PLN/fertiliser use in 1000 kg)</td><td>Land productivity (the ratio of agricultural output in thou. PLN/utilised agricultural area in ha)</td></tr>
<tr><td>Fertiliser efficiency (the ratio of agricultural output in thou. PLN/expenditure on fertilisers in thou. PLN)</td><td>Labour productivity (the ratio of agricultural output in PLN/number of person-hours worked on a farm)</td></tr>
<tr><td>Energy efficiency (the ratio of agricultural output in thou. PLN/expenditure on energy in thou. PLN)</td><td rowspan="2">Capital productivity (the ratio of agricultural output in PLN/the value of total assets in PLN)</td></tr>
<tr><td>Thermal insulation of livestock buildings (dummy variable: 1 = yes; 0 = no)</td></tr>
<tr><td colspan="2">Additional variables:
Agricultural income in thou. PLN
Land value in thou. PLN
Share of agricultural income in household’s total income (in %)</td></tr>
<tr><td colspan="2">Main relationships (max. 1):
Impact of productivity on low-carbon agriculture: positive (0.72)
Productivity & income: positive (0.89)
Productivity & share of agricultural income in household’s total income: positive (0.32)</td></tr>
<tr><td colspan="2">Additional interactions (max. 1):
Land productivity & capital productivity: positive (0.32)
Land productivity & low-carbon agriculture: positive (0.49)
Labour productivity & low-carbon agriculture: positive (0.6)
Fertiliser use efficiency & fertiliser efficiency: positive (0.9)</td></tr>
</table>

Source: based on (Borychowski et al., 2022).

Low-carbon agriculture can be defined as an agricultural system which enables efficient production of materials, food, feed and fibres while reducing energy inputs and greenhouse gas emissions from agriculture, following the principles of sustainable development (Piwowar, 2019). It shall be clearly indicated that it is possible to simultaneously achieve both economic and environmental goals (Table 2.2). Our results are consistent with other authors’ findings. Rafiq et al. (2016) confirmed that energy intensity is an important driver of pollution emissions; thus, increasing energy efficiency promotes low-carbon agriculture. Iram et al. (2020) also showed the importance of energy efficiency for environmental performance and carbon emission reduction. Piwowar (2019) additionally specified that improving energy efficiency in Polish agriculture should relate to lowering fuel consumption. Similarly, other authors emphasised the role of increasing fertiliser efficiency in moving towards low-carbon agriculture (Koondhar et al., 2021; Piwowar, 2019)

Conclusions

The research conducted allows to formulate the following conclusions and recommendations:

- There are significant mutual and positive relations between the economic, social and environmental spheres within the analysed farms. Thus, those relationships can be complementary to each other. In practice, this means that to promote sustainability in the social and environmental dimensions, income and capital are needed to finance pro-environmental actions and to improve well-being in the social sphere (better meeting consumption needs, providing education). By supporting one dimension of sustainability, other dimensions can also be improved, assuming the existence of a certain system of environmental and social protection. The strongest positive relationship was observed between the economic and environmental dimensions, which may come as somewhat surprising. It has been noted that the adoption and promotion of best farming techniques, eco-innovation and services which require capital are associated with improving environmental performance (Van Grinsven et al., 2019). This finding is further supported by our research, which indicates that resource productivity plays a crucial role in determining a low-carbon economy within farms. Therefore, qualitative factors such as production techniques and implementation of innovations to create a low-carbon economy hold significant importance for both the environmental and economic dimensions of farms. Within the economic dimension, the value of output and income exhibited the most positive associations, while assets were given relatively less significance. This observation could be attributed to the capitalisation of subsidies in agricultural land prices, influencing the relative importance of assets in the economic dimension. At the current stage of development of the EU countries, the evolution of the CAP support instruments tends to put increased emphasis on the environmental context of the agricultural support mechanism and on developing a low carbon-economy. To achieve this goal, the CAP support should be more closely linked to environmental investments. Green investment grants could support using alternative energy sources (biogas plants, photovoltaics), thermal modernisation of buildings, elimination of old types of furnaces. Thus, there is a need for further increasing the support of the environmental component in the functioning of agricultural holdings. We mean here also building farmers' awareness of these issues through education and training.
- As regards the social dimension of functioning of farms, it is important to further promote the economic and social infrastructure and improve the education of agricultural producers. It results from the fact that the social dimension is economic in nature.

- Climate change will stimulate environmental issues as well as low-carbon economy in the functioning of farms to a greater extent. This may facilitate a balance between the economic, social and environmental fields. Further research in this area should take into account externalities as well as provision of public goods by farms. The results of such research would help to identify other determinants that shape the relationships between the economic, environmental and social dimensions of the sustainability of farms. It would be interesting to conduct similar research in regions with different levels of agricultural development.

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3. DIGITALISATION IN AGRI-FOOD SECTOR

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Abstract

The progress of the Fourth Industrial Revolution (called Industry 4.0) is driven by the development of cutting-edge digital technologies. Digital transformation is changing not only the manner of production, but also the definition of quality and the manner of quality management. The idea of Quality 4.0 refers both to the development of new technologies for quality assurance and control, as well as to changes in the culture of quality management. Industry 4.0 technologies are increasingly used in food production, leading to the development of Agri-food 4.0. They serve, for example, to control and implement production using automatic machines and robots. Invasive or remote sensors are used to monitor the environment, crops, farming conditions, processing operations and products throughout the entire supply chain. The use of the Internet of Things, artificial intelligence, big data and cloud computing enables advanced planning, control and optimisation of production. The use of digital technologies in the agri-food industry positively affects the quality and safety of food and has a positive impact on the efficiency of enterprises. At the same time, digital transformation is an opportunity to develop sustainable practices throughout the food supply chain. In this chapter, we present the idea of Industry 4.0 and Quality 4.0 as well as examples of the use of digital technologies in the agri-food sector.

Keywords: Industry 4.0, Quality 4.0, Agri-food 4.0, digitalisation, quality management.

JEL codes: O14, Q01, Q16.

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Introduction

The modern food industry is a very competitive and dynamically developing environment in which consumer demands are growing towards better quality, safety and durability of food, greater variety of products and adoption of sustainable production. Therefore, in order to meet the ever-increasing consumer demand for high-quality food products, food researchers and the food industry should constantly look for more advanced solutions and technologies, including innovative processing and analytical techniques.

In the food industry, the ongoing Industry 4.0 era is characterised by high interconnectivity and the growing use of new technologies, especially digital innovations. The European Union countries have adopted Industry 4.0 technologies in very different ways. Due to their Industry 4.0 infrastructure and big data maturity, the Netherlands and Finland are leading in the implementation of Industry 4.0, while Hungary, Bulgaria and Poland come last (Castelo-Branco et al., 2019).

Advanced technologies have accelerated digitalisation and automation in almost all sectors, including the agriculture and food industry (Hassoun, Aït-Kaddour et al., 2022). Food producers can use technological approaches to solve problems such as food safety and quality, production optimisation, traceability, shelf-life control and other related issues in the context of food production. The integration of digital technologies in the food supply chain supports sustainable development in the agri-food sector.

The application of digital technologies in agriculture and food production sectors has been referred to using terms such as Agriculture 4.0, Digital Agriculture, Smart Agriculture 4.0, Smart Farming 4.0, Smart Farming (Calafat-Marzal et al., 2023). The term Agri-food 4.0 usually refers to the entire food production chain, from agricultural practices to food consumption (Calafat-Marzal et al., 2023). Smart Agriculture is defined as a management concept that directs actions to protect or increase agricultural productivity and food security in the face of changing physical and chemical constraints, changing climate and increasing requirements or expectations for transparency towards all actors in the agri-food chain (Baerdemaeker, 2023).

Recently, Hassoun et al. (2022) provided a general overview of key Industry 4.0 principles and their application in food production. According to Demartini et al. (2018), Hassoun, Jagtap, Garcia-Garcia et al. (2023), the number of publications and citations related to digitalisation or automation in the agri-food sector has increased tremendously in the last decade, and it is still rising; these issues have been presented in several reports (Baerdemaeker, 2023; FAO, 2022; McFadden et al., 2022).

This chapter briefly presents the idea of Industry 4.0 and Quality 4.0 as well as the examples of applications of cutting-edge digital technologies in the agri-food sector.

3.1. Digital transformation and evolution of quality concept

The Fourth Industrial Revolution is a modern idea that leads organisations into a new era of robotisation and digitalisation through optimal control of all production processes. The Industry 4.0 concept is currently one of the most-discussed topics among practitioners and scientists, making it a priority for many research institutions and enterprises (Bigliardi et al., 2023). In Industry 4.0, the manufacturing operations systems are increasingly deeply integrated with communication, information and intelligence technologies. These technologies can be categorised into physical and digital. Physical technologies mostly refer to manufacturing technologies such as: additive manufacturing, sensors and drones, while the digital ones refer to modern information and communication systems, such as: cloud computing, blockchain and big data (Bai et al., 2020). Various industrial sectors, including the food industry, are increasingly adopting the Industry 4.0 technologies (Hassoun, Jagtap, Trollman et al., 2023).

Past industrial revolutions not only changed the way products were made, but also affected the way their safety and quality were evaluated. Figure 3.1 presents the transformation from Quality 1.0 to Quality 4.0.

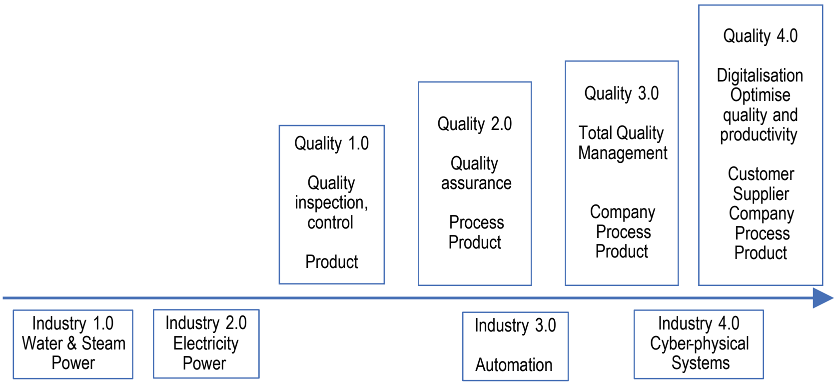

Figure 3.1. Evolution from Quality 1.0 to Quality 4.0
Source: based on (Liu et al., 2023; Zulqarnain et al., 2022).

As shown in Figure 3.1, companies have changed their approach to quality over time. Initially, manufacturers focused on plant productivity without focusing on losses. Product quality was a secondary issue that was assessed by time-consuming measurements.

In the Quality 2.0 era, this approach changed, and manufacturers began to pay attention to the waste generated. Labour productivity also became an important issue, which manufacturers sought to optimise. However, maximising production was still the most important issue of the era (Zulqarnain et al., 2022).

The next period called Quality 3.0 was a period in which quality was a key aspect of the business. During that era, organisations emphasised meeting customer requirements so that they were satisfied with the goods they purchased. Companies strived for continuous improvement, increasing productivity through appropriate labour and production standards (ISO standards) and involved all employees in activities that affected quality. In that era companies adapted Total Quality Management (TQM) to better manage quality strategies. Those activities reduced company costs resulting from advertised goods and production errors (Broday, 2022).

The solutions emerging from the Fourth Industrial Revolution have forced the transformation to Quality 4.0. There are various definitions given by different authors of Quality 4.0 which were presented by Broday (2022). Based on Carvalho et al. (2021), the term Quality 4.0 can be characterised as "the digitalisation of TQM and its effect on quality technology, processes and individuals". In the past, total quality management (TQM) and statistical control charts were used to enhance processes and inspect products for flaws. Quality 4.0 is the digitisation of quality management, fusing the new capabilities of Industry 4.0 with the established techniques of quality control. As a result, businesses need to modify their corporate cultures to put more emphasis on design, safety and service quality (Broday, 2022). Quality 4.0 technologies enable manufacturers to control quality throughout the production process. Based on Li et al. (2019), the real-time quality assurance with detailed documentation is available to organisations at every step of the process. According to Hyun Park et al. (2017), new industrial 4.0 technologies can help achieve quality excellence. Robertsone and Lapiņa (2021) explored how digital transformation changes quality management practices adopted by organisations. The scientists point out that there are several tasks and goals for the quality management, which organisations should take care of. In their study, the authors found that certain quality management practices become essential as prerequisites for digitalisation and for successful digital transformation, while other practices are influenced and affected by digitalisation.

Furthermore, artificial intelligence and big data analytics can be used to manage quality in companies. However, projects based on these technologies are not widely implemented in practice, and quality leaders do not use solutions based on the idea of Quality 4.0. Escobar et al. (2021) proposed a novel seven-step problem-solving strategy that includes the following steps: identify, acsensorise, discover, learn, predict, redesign and relearn. According to the authors, such a comprehensive approach increases the likelihood of successful implementation of the Quality 4.0 initiative.

3.2. Digitalisation and sustainability opportunities

Sustainable growth has become an important issue for companies in recent years. Additionally, there is a growing interest in the scientific literature concerning the impact of Industry 4.0 technologies on sustainable management and production (Ejsmont et al., 2020). Industry 4.0 has a great potential to increase resource efficiency while achieving sustainable value creation across social, economic and environmental dimensions (Calafat-Marzal et al., 2023; Carmela Annosi et al., 2020; Ghobakhloo, 2019; R. Sharma et al., 2021).

Based on Stock and Seliger (2016), there are some opportunities of sustainable manufacturing for the micro and macro perspectives of Industry 4.0. For the macro perspective, there are two main opportunities of sustainable manufacturing:

- selling the functionality and accessibility of products rather than just the tangible products,
- effective coordination of product, material, energy and water flows throughout product life cycles as well as between different factories.

For the micro perspective, there are five main opportunities of sustainable manufacturing:

- upgrading existing equipment to implement production monitoring sensors which will control, for example, energy efficiency,
- new skills of workers and better human performance,
- efficient use of resources, including water, energy and goods,
- designing suitable production process chains,
- adding new services to the product in order to improve customer satisfaction.

According to Bai et al. (2020), there are three main dimensions where Industry 4.0 technologies improve sustainability. The first one is the economic dimension, where organisations can reduce set-up times, labour and material costs, and increase productivity. The second dimension is the ecological point of view, where technologies can help in reducing energy, CO_2 emissions and waste. The third dimension is focusing on social sustainability. Employees are supported by smart and autonomous production systems to achieve better performance, higher satisfaction and motivation.

3.3. Digital technologies used in agri-food sector

Digital transformation in the agri-food industry is based on the adoptation of Industry 4.0 technologies. Enabling and high-impact applied technologies such as automation, autonomous robots, the Internet of Things (IoT), radio frequency identification (RFID), smart sensors, big data, artificial intelligence (AI), machine learning (ML), cloud computing and blockchain are increasingly used in food production (Hassoun, Jagtap, Garcia-Garcia et al., 2023) (Figure 3.2).

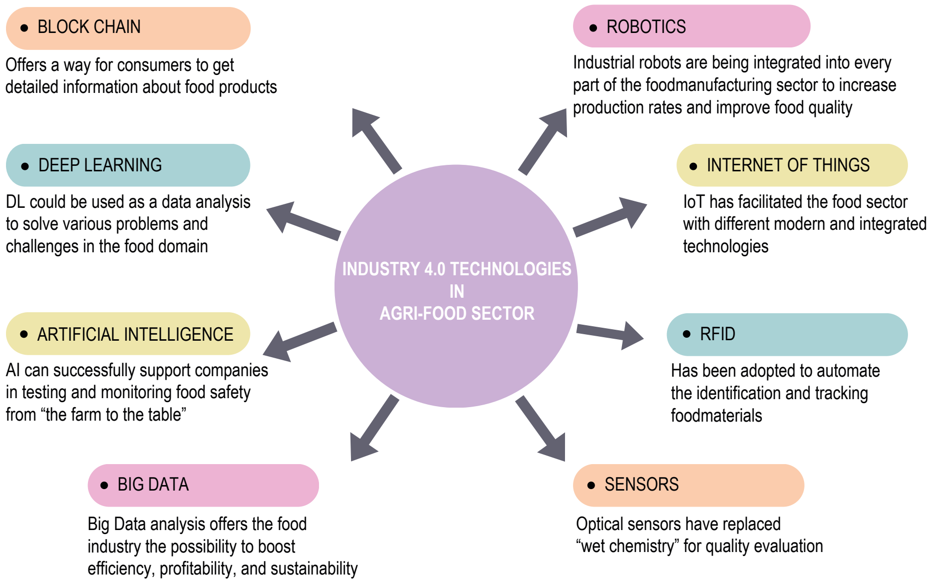

Figure 3.2. Diagram of digital technologies used in agri-food sector
Source: based on (Hassoun, Jagtap, Garcia-Garcia et al., 2023).

Nowadays robotics has started to make its way into almost every link in the food supply chain, "from farm to table" (Wang & Wang, 2021). On the farm, robots are used to help farmers plant, identify and sort seeds. They also monitor seedling growth and spray water. Autonomous vehicles (tractors) and drones are used for harvesting, monitoring and analysing crops (Wakchaure et al., 2023). In food manufacturing, robotics is used in primary and secondary processing—raw food is washed, sorted, transported, sliced and blended, while ingredients are combined to create new food products through cooking, baking, mixing, etc. (Iqbal et al., 2017). Robotics is also used in food packaging as pick-and-place robots (Mahalik & Nambiar, 2010). In the three final stages: delivery, serving and cooking, robots are still under development and need improvement (Iqbal et al., 2017).

The Internet of Things is another key 4.0 technology. IoT has facilitated the food sector with different modern and integrated technologies, such as: smart sensors, RFID, communication technologies and Internet protocols (Shah & Yaqoob, 2016). Due to the complexity of current technologies, smart sensors based on wireless technologies have been under rapid development in recent years and play a significant role in data acquisition and process automation in food industry

(Miranda et al., 2019). To improve the control in food processing, sensors are implemented in various stages of processing lines. Such solutions enable better process management, which consequently reduces the loss of food quality and production costs (Franceschelli et al., 2021).

The Radio Frequency Identification (RFID) has been adopted in the food supply chain as to automate the identification and tracking of food materials (Ilie-Zudor et al., 2011). According to Noor Hasnan & Yusoff (2018), a great example of the RFID application could be chicken meat, where the system is applied through a complete chain from the farm, through a slaughterhouse and processing factory, to the retailer.

One of the most important areas is the digitalisation of food quality control. To ensure that food products are safe for consumers and have the required organoleptic characteristics, quality control is key in the food sector. Quality is defined by several attributes, including the nutritional value, physicochemical properties, safety, sensory characteristics and shelf life. Originally, food quality was assessed using a variety of destructive and laborious techniques with limited analytical performance. Automated instrumental techniques have replaced "wet chemistry" in recent years. Based on Misra et al. (2022), food quality can be assessed by spectroscopic sensors and hyperspectral cameras, which are used more commonly nowadays for food quality and safety monitoring. To meet the demands of the food sector, smaller and faster devices (sensors) are being developed, allowing manufacturers to use them more efficiently throughout the production process. Relevant datasets from sensors can be grouped in the cloud and explored to help regulate quality standards as part of Industry 4.0 (Misra et al., 2022).

The food industry has huge potential for applying big data solutions to improve their businesses. In farming, a lot of data is generated by sensors which are analysed by farmers to help them make the right decisions (Wolfert et al., 2017). According to Jin et al. (2020), satellite imagery data can be used to detect crop growth, harvest prediction and improve agriculture monitoring systems, thereby helping to improve the quality of agriculture products. Big data is also useful in food logistics where obtained information are used for planning routes and choosing the best method of transportation (Jagtap et al., 2021). Furthermore, Big data can be also used to provide food safety solutions (Sadiku et al., 2020).

The next digital technology which is becoming crucial in recent years in food industry is artificial intelligence (AI). Based on Kler et al. (2022), the data management for food safety and quality may be changed with the use of machine learning and AI which may streamline the entire process. According to Bai et al. (2020), to effectively manage the whole supply chain and the associated human activities, all stakeholders must concur on the data to be recorded in a blockchain, from raw materials to final products. Yang et al. (2022) showed that the machine vision technology integrated with AI can be used for sorting apples according to their characteristics. This technology not only improves the sorting efficiency but also reduces damage to apples. In the supply chain management, AI can successfully support companies in testing and monitoring food safety from “the farm to the table” (Chacón Ramírez et al., 2020). According to Di Vaio et al. (2020), artificial intelligence has great potential to reduce waste and improve process efficiency to create more sustainable food production.

Deep learning (DL) could be used as a data analysis tool to solve various problems and challenges in the food domain. Zhu et al. (2021) presented in their paper how traditional machine learning and deep learning methods could be applied to the fields of food processing. Zhou et al. (2019) demonstrated that DL could be used for food traceability, calorie estimation, quality assessment of fruit, vegetables and meat. Following the authors, DL has been successfully applied for detecting food fraud and contamination.

The traceability of food is an important factor that indicates its quality (Yu et al., 2022). To ensure a new, higher level of food traceability, it is predicted that blockchain technology will be integrated with AI and big data as well as cloud computing to provide consumers with transparent information about the product’s origin (Hassoun, Jagtap, Garcia-Garcia et al., 2023). In food packaging, AI solutions can help reduce the environmental impact of food packaging by optimising the design of packaging materials (Hassoun, Jagtap, Garcia-Garcia et al., 2023).

3.4. Challenges of digital transformation

Digital technologies could be incorporated into the agri-food sector to digitalise it and improve process stability, productivity and product customisation. However, there are still some challenges that companies (not only in the food industry) have to face in order to implement these new technologies (Carmela Annosi et al., 2020; Sharma et al., 2023).

The main challenges are the following.

a. Technical and technological challenges: complexity and technical challenges are the biggest barriers for companies that want to undergo digital transformation of their facilities (Microsoft, 2021). Current machines are not network-ready, which requires them to be adjusted or replaced accordingly.
b. Lack of budget and knowledge: most companies complain that a lack of budget and well-skilled staff have stopped the digital implementation in their organisations. Digitisation and the associated changes in machines, software as well as training for employees generate costs (up-front investments and recurring maintenance expenses) that many organisations are not prepared for (McFadden et al., 2022).

c. Information security and data protection: one of the main Industry 4.0 adoption barriers is corporate concerns about information security and privacy. Nearly a third (29%) of organisations believe that security risks associated with the implementation of IoT outweigh any potential benefits (Cisco, 2016).
d. Standardisation issues: the most significant concerns about data created in the supply chain are connected with issues of data justice, data quality and a lack of standardisation (Jin et al., 2020).

In order to remove barriers and support the implementation of digital technologies in the agri-food sector, it is necessary to take appropriate measures, e.g., informing people about their benefits, including intangible benefits, related to improving the quality of life and reducing the negative impact of food production on the climate. It is important to invest in human capital and strengthen the sector with well-trained professionals who are proficient in disruptive technologies, as well as to introduce the right incentives for innovation. Public and private policies should foster knowledge and data sharing to strengthen inclusive, secure and representative data ecosystems and promote competitive markets (Calafat-Marzal et al., 2023; McFadden et al., 2022).

Conclusions

The implementation of Industry 4.0 technologies could lead to huge time and cost savings compared to traditional processes. The topic of digital transformation of the agri-food industry is of great interest nowadays. Various types of robots are used in the food industry to improve production and reduce labour. For instance, smart spectroscopic-based sensors have been developed to enhance food quality. The food processing sector is also becoming more familiar with the IoT and other associated technologies to reduce waste and costs. Furthermore, big data also offers many benefits, including food traceability and safety. Undoubtedly, there are still numerous challenges that companies need to face, but in the end, the implementation of new Industry 4.0 technologies offers an interesting and sustainable approach to enhance food production from “farm to fork”.

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4. PACKAGING SUPPORTING FOOD SUSTAINABILITY

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Abstract

The chapter generally presents a new approach to the design of packaging and packaging materials that supports food sustainability. Concern for environmentally friendly packaging and packaging materials drives the development of their design for recycling and increasing popularity of reusable packaging. Food sustainability is also one of the main prerequisites in the packaging optimum approach and ensuring product accessibility via its packaging applied in the supply chain. Active packaging systems allow for extending the shelf life of food, and intelligent packaging supports the reduction of food waste and losses. Modern solutions for automatic data collection, such as RFID tags and geolocation systems, can also support the management of data on food products in logistics. The chapter presents successively new approaches to packaging design, design for recycling, reusable packaging, and smart packaging solutions supporting food sustainability.

Keywords: sustainable packaging design, packaging materials, active packaging, intelligent packaging, design for recycling.

JEL codes: L69, O39, Q01, Q56, Q59.

Introduction

Providing the population with food is one of the main tasks of the economy, both locally and globally. Economic activity, including food supply, is associated with costs and possible burdens for the environment. Especially the latter are particularly considered in the implementation of the sustainable development policy. The food supply chain is inextricably linked to the use of packaging as well as product labelling systems (Otto et al., 2021).

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Traditional functions of food packaging encompass the preservation of food from contamination and undesirable environmental conditions, as well as maintaining its freshness and quality, which leads to ensuring the product shelf life (Siracusa & Lotti, 2019). Further tasks for packaging relate to communication of required information about the product (e.g., nutritional content, expiration date), its storage and consumption conditions. Packaging also provides the convenience of product handling both by the consumer and other participants of the supply chain, which is also related to food containment (Kuswandi & Jumina, 2020). To support food sustainability, conventional packaging had to evolve in areas of waste preservation, logistic process optimisation, recyclability and reuse of materials. This meant recognition of new criteria in the design, which should be environmentally conscious to reduce the impact of both packaging waste and food loss (as well as food waste).

The differentiation between food loss and its waste is not firm and based on the recognition of the stage of the food supply chain involved in this adverse event. Food loss occurs in the stages of the food supply chain present before the product reaches the consumer. It is mainly related to food preparation and post-harvest processing (Ishangulyyev et al., 2019). It could be referred to losses caused by the evaporation of water and volatile substances, mismatch between transport or storage conditions and food requirements as well as sorting losses. Food waste refers to the losses resulting from the actions and decisions of the consumer that take place during the distribution and consumption of food (Conrad & Blackstone, 2021). Consumers, knowingly or unknowingly, generate huge amounts of food waste as a result of their neglect of food's suitability for consumption, accumulation of excess stocks or irresponsible purchase of unnecessary products. Table 4.1 shows examples of food losses and waste that can occur in the supply chain and how packaging can support food sustainability.

Packaging plays a very important role in the food supply chain and has great potential to reduce food losses and reduce food waste (Ganeson et al., 2023). Many sources of food loss/waste in the supply chain have the basis in inappropriate stock management, packaging mismatches and bad communication concerning the properties of packaged products. The packaging design can ensure a sustainable approach to both food products and their packaging, limiting the waste of resources and reducing the negative impact on the environment.

Perishable food with a short shelf life can easily become waste if it is not stored properly or the best-before dates are missed. The reduction of food waste could be facilitated by the introduction of active packaging technologies focused on their additional capabilities to directly enhance or maintain food quality. An additional advantage of active packaging application could be the reduction of food processing and chemical preservation, which supports sustainable food production. Absorbers (scavengers) can remove chemical substances that adversely affect the

Table 4.1. Potential food loss/waste in the food supply chain and possible packaging support for food sustainability

Food supply chain stages	Potential food loss/waste	Packaging support for food sustainability
Agricultural production and harvest	• improper post-harvest treatment and storage of food raw materials (e.g. mechanical damage, microbial contamination, field or barn loss)	• bulk packaging and protection against contamination (raw material loss) • reusable containers and packaging adapted to the supply chain
Food processing, packaging and storage	• food loss, damage and/or contamination during processing and packaging filling • incorrect selection of packaging in relation to product properties • over/underestimation of shelf life of packaged food in relation to specific storage conditions	• food preservation in packaging or product portioning in barrier-tight packaging systems • matching the packaging to the food product's storage and transport susceptibility—packaging optimum approach • active packaging extending food product shelf life
Food transport and wholesale distribution	• packaging failure/damage in distribution • multiple handling of raw food products • excess stock (oversupply) and/or poor stock rotation	• identification and tracking of supply chain losses • system packages and reusable containers adapted to the supply chain • intelligent packaging and data sharing within the supply chain
Retail or HoReCa supply	• food perishing in distribution and after sale • mismatch of the product portion to the final recipient (e.g., inedible portions)	• recognition of customers' shopping/eating habits and matching of food packaging • designed multiuse/refilled packaging or food distributors before final consumption • retail ready packaging
Final consumer storage and food consumption	• missed food expiration dates • food remnants left in packaging • inappropriate food packaging capacity	• accessible packaging design • packaging designed for recycling • intelligent packaging for consumer application

Source: based on (Ganeson et al., 2023; Verghese et al., 2013).

packaged product, emitters introduce the desired substances, while antimicrobial substances—also present in active packaging—limit the growth of undesirable microorganisms (Carvalho et al., 2021).

On the other hand, the reduction of food waste can be supported by the use of intelligent packaging and modern automatic data collection (ADC) systems. Intelligent packaging systems are able to indicate the real state of packed food (ripeness or spoilage) and monitor the environmental conditions that affect the product's shelf life (Schaefer & Cheung, 2018).

The choice of proper packaging supporting the sustainability of food products requires fast and reliable collection of information on products appearing in the supply chain. Automatic Data Collection (ADC) systems based on barcodes placed on the packaging allow for quick gathering of information about the packed foods and their properties. Even more efficient collection of information about the products can be ensured by the introduction of packaging equipped with optical 2D codes (e.g. QR codes) or RFID (Radio-Frequency Identification) tags.

4.1. New approaches to packaging design

Most products offered on the market are sold in packaging. To date, the approach to the packaging design process has largely been based on voluntary standards and sanctioned by regulations within a rather narrow scope, i.e. related to ensuring product and consumer safety. Many aspects with regard to the selection of packaging materials, the size and shape of the packaging, the method of printing and decorating or the choice of closing systems are left to the discretion of manufacturers and brand owners. Packaging has become an excellent tool for building competitive advantage in the market but with a whole range of (negative) consequences.

Designing optimal and sustainable packaging should balance ensuring product protection with the minimal negative environmental impact of packaging. This requires adequate packaging methods and systems, the ability to make improvements and innovations in transportation and distribution processes, the introduction of new sales and marketing concepts, as well as an efficient collection and recycling system. Innovations introduced at one stage may not cause hindrances at subsequent stages but can be the initiators of positive changes (Jepsen et al., 2019).

Designing packaging, or deciding to partially or completely eliminate it, must never conflict with consumer, product and environmental protection. The key protective function of the packaging must be maintained and ensured at an optimal level. The word "optimal" is used intentionally here because any packaging requires using resources for the packaging, and underpackaging or overpackaging will have a negative environmental impact (Jepsen et al., 2019).

Designing in terms of optimal resource utilisation aims to protect the product and minimise the number of waste streams introduced. For years, brand owners have been accustomed to using richly decorated packaging, multi-material laminates with very high barrier properties, thick and rigid packaging delivering excessive properties, without asking themselves what kind of packaging the product requires and what the customer expects.

"Ecodesign" or "sustainable packaging design" is based on multiple principles, the most important of which are presented below. The ecodesign process should:

- encompass holistically the packaging design and implementation process from a supply chain perspective,
- identify processes and relationships directly and indirectly related to packaging,
- predict and analyse the benefits and costs of marketing packaging,

- fit in and conform to the assumptions of the circular economy sanctioned by European Union policies and regulations,
- fit into the canon of good market practices oriented towards reducing the generation of packaging waste and eliminating impediments to mechanical recycling,
- conform to the packaging waste hierarchy, be recyclable in practice and on a large scale, as well as use recycled materials as much as possible,
- protect the product and prevent product loss and waste,
- provide convenient, user-friendly and safe solutions that take into account the needs of different user groups (accessible design),
- communicate high-quality, understandable, verified, reliable, relevant and timely environmental information (Jepsen et al., 2019; ISO 14021:2016, 2016; PPP, 2022, 2023).

A new approach to packaging selection and design should be based on the three pillars: elimination, reuse and material circulation (Ellen MacArthur Foundation, n.d.), and should focus on reinventing the role of packaging along with the reasons for its use. The design of packaging accompanying consumers over the past 20–30 years has reinforced the belief that better packaging means a better product. Moving beyond this pattern requires a change in the directions and mindsets not only of designers and brand owners but also of consumers themselves. The new era in packaging design starts by breaking down the packaging design patterns that have been duplicated so far, and prompts questions about the context and business model for delivering products and services to consumers in such a way that they have value for consumers and users, but at the same time reduce packaging waste on a global scale (Ellen MacArthur Foundation, n.d.).

Implementing change and upstream innovation in the packaging industry is not intended to take value away from products or limit their usefulness or marketability, but to achieve the desired effect by implementing new design tools and finding solutions. This can be done by verifying packaging at three levels:

1) business model analysis and verification of social, environmental and economic benefits—supply chain model, geographic coverage of the system, verification and fulfilment of the needs of user groups and the types of packaging and ancillary products used; use of volume packaging, introduction of in-home or station filling systems, use of returnable packaging, sale of products in bulk or filling of own containers, introduction of collection or exchange points (Ellen MacArthur Foundation, n.d.; PN-EN 13429:2007);
2) analysis of the product and the way it is sold and delivered—refers to the analysis of the recipe and the content of certain ingredients (including water content or fillers), the shape, size and actual amount of the product that users need and expect; in this area, it is possible to achieve a change in the physical state of the product or to reduce certain elements of the packaging due to

the transmission of digital information about the product (Ellen MacArthur Foundation, n.d.);

3) verification and reinvention of the design of the packaging based on the needs of users and to ensure the safety of the product—such analysis should verify the reasonableness of all packaging components and elements (including their weight, thickness, strength, barrier properties, etc.), materials from which they are made, size of the packaging and the ratio of the weight of the packaging to the product, void space, method of opening, dispensing and access to the contents, packaging components and their role as well as the possibility of their elimination, ease of sorting the packaging waste, compatibility with collection and segregation systems and recycling processes (mechanical, biological, chemical), as well as the possibility of using recyclables in closed and open loops (PPP, n.d.; Ellen MacArthur Foundation, n.d.).

4.2. Design for recycling

Packaging placed on the market must be designed and made in such a way that it can be reused and subsequently recycled, or at least recycled if reuse is not possible, or offer a form of recovery other than recycling if recycling is not possible (Act of 13 June 2013). This should be evaluated in terms of compliance with European harmonised standards for packaging design, which should meet at least three main criteria:

1) concerning production and composition (PN-EN 13428);
2) concerning reusability (PN-EN 13429);
3) concerning recovery: by material recycling (PN-EN 13430), energy recovery (PN-EN 13431) or organic recovery (PN-EN 13432).

Packaging design for recycling is one of the elements of packaging design with its full life cycle in mind, but the recyclability of packaging materials ensures their circularity (Act of 14 December 2012; Act of 13 June 2013; Act of 14 April 2023). This impacts future recycling targets (Regulation of the Minister of Climate and Environment of 19 December 2021) and the obligation to use recyclables in packaging placed on the market. As defined in Regulation 2022/1616, "'recycling technology' means a specific combination of physical or chemical concepts, principles and practices to recycle a waste stream of a certain type and collected in a certain way into recycled plastic materials and articles of a specific type and with a specific intended use, and includes a decontamination technology" (Commission Regulation (EU) 2022/1616).

Proper packaging design using different materials requires knowledge of collection, sorting, identification and processing technologies, as well as barriers affecting elimination from the process, reduction in the quality of recyclates obtained, or negative impacts on other materials in the stream.

The first stage is the collection of packaging waste from users, i.e. consumers (Post-Consumer Waste, PCW) or manufacturing companies (Post-Industrial Waste, PIW). This waste generally differs in its homogeneity, degree of soiling, as well as identifiability of materials and their properties. Consumers in Poland are required to sort packaging waste into five different fractions: paper, glass, metals, plastics, multi-material packaging waste and bio-waste (Regulation of the Minister of Climate and Environment of 10 May 2021). The quality of sorting by consumers largely depends on consumers' familiarity with packaging materials and signs on packaging indicating the type of material and/or additional information to facilitate sorting (Regulation of the Minister of Environment of 3 September 2014). The level of actual knowledge of Polish consumers regarding the guidelines for waste sorting is insufficient (Wojciechowska & Wiszumirska, 2021), resulting in the loss of valuable packaging waste that does not reach recycling streams from the mixed waste.

The collection stage is followed by further industrial processes of pre-sorting, identification, washing/cleaning and processing. The quality and efficiency of processing are influenced by the first stages of the process, i.e. pre-sorting and screening of contaminants and traceability. Sorting and screening of contaminants involve classifying materials by size. A drum screen used here is the most common method of sorting, which can reject parts with dimensions of less than 20–50 mm. These are fine organic and inorganic contaminants. In the case of sorting plastic waste, nuts, small labels or small flexible packaging also end up in the subscreen fraction. Thus, small-sized packaging or components detached from the main packaging may be rejected early in the process. The next stages of identification take advantage of different technologies (e.g., manual sorting, magnetic and eddy current separation, optical sorting or other technologies, such as X-ray). Each waste stream has different requirements and barriers. The most important examples are briefly discussed below.

4.3. Reusable packaging

Today's consumer is accustomed to the use of disposable packaging because its production is affordable and perfectly integrated into everyday consumption and business models. "Business as usual" has so far not given due consideration to the circularity of resources in the economy. The dominant linear ("take-make-dispose") economy creates value by mass-producing and selling as many products as possible. The circular economy is guided by the 3Rs principle (reduce, reuse, recycle). The difference in the two approaches (linear and circular) lies largely in resource efficiency in the circular model (reduce), maximising the use of products through their extended life cycle (reuse) and returning valuable raw materials through efficient, accessible, effective and safe recycling systems (recycle). The change in attitude towards the use through elimination, reuse, product-service swaps, repairability or regeneration and other models will increase eco-effectiveness. Reusable packaging is an excellent example of this; however, it is worth noting that it is not a remedy for the environmental problems caused by packaging waste and that it is one of the options available, which requires consideration of environmental, social and economic benefits and costs.

The design of reusable packaging and reuse systems must comply with current legal requirements, which indicate the framework and limits of their use in a given market. Reusable packaging design is second in the European waste hierarchy (right after prevention), which means it should be taken into consideration before choosing single-use packaging (Directive 2008/98/EC). The definition of "reusable packaging" includes several conditions that the packaging must simultaneously meet, including: design criterion, market criterion, usability criterion, end-of-life criterion (Act of 13 June 2013; Commission guidelines, 2021).

Reusable packaging is a cohesive part of the system. Based on PN-EN 13429:2007, three reusable systems can be distinguished: closed loop, open loop and mixed loop. In the closed loop system, packaging rotates within a single company or a group of cooperating companies. In the open loop system, packaging circulates between unspecified companies. On the other hand, the mixed loop system additionally uses disposable packaging, which acts as an auxiliary product, and reusable packaging remains the property of the end user.

To maximise the benefits of reusable packaging systems, it will be necessary to change the approach of broader packaging design. Paradoxically, reusable packaging may consume more resources than lightweight disposable packaging (per unit of packaging), but both the materials and their management systems should reduce the number of raw materials used and waste (including packaging) generated in the long run. In addition, the specific requirements for packaging design may change depending on the system in which the packaging operates.

The criteria for the operation of the mixed system, which assumes that the person emptying the packaging is also the filler who uses another disposable packaging for this purpose (e.g., refill at home), do not fit into the new legal perspective and do not prevent waste (PPWR, 2023). Instead, a refill station is proposed, where consumers can buy a product and refill their packaging with the same product or choose from a range of several products.

The refill/reuse models will enable new insights into the use of materials such as metals, glass and plastics. Reusable packaging must be designed to achieve a longer shelf life and a target number of rotations, as well as to be compatible in the stages of refilling, cleaning and disinfection, collection and return, and finally, be recyclable in practice and on a large scale.

To see the broad perspective of the innovation of reuse models and available solutions, it is worth looking at several solutions that offer product return or refilling systems (Ellen MacArthur Foundation, n.d.).

These considerations primarily apply to business-to-consumer (B2C) solutions, but this system also benefits the business-to-business (B2B) level, and there are many well-functioning solutions on the market. Transportation packaging and infrastructure should be standardised across the system, and some solutions can be offered as a service. Smart labelling, identification and tracking systems are also used throughout the supply chain to help optimise costs and logistics, such as the CHEP Pooling System based on the concept of "share and reuse" (CHEP, n.d.) or REUSA-WRAPS for reusable pallet wraps (REUSA-WRAPS, n.d.).

4.4. Smart packaging solutions supporting food sustainability

4.4.1. Active packaging systems extending the shelf life of food

Food shelf life is a derivate of such factors as the selection of raw food materials (suitable for treatment and/or storage), processing them with physical and/or chemical methods, as well as their recommended storage and transport conditions (including packaging selection) (Soro et al., 2021). The need for packaging applications originates from its practical aspect of holding a certain amount of food together and protecting it within the supply chain. According to FAO reports, about 14% of food products are lost in the supply chain before they reach the final consumer (FAO, 2019). Protection against adverse physical conditions as well as chemical and/or microbial contamination is a result of the barrier capabilities of packaging construction and its materials, which is a passive (conventional) way of product preservation against external factors (Schaefer & Cheung, 2018). Active packaging systems are developed to effectively influence packed food and/or its surroundings, which results in the extension of food shelf life.

European legislation, i.e. Commission Regulation (EC) No 450/2009 of 29 May 2009 (Regulation (EC) No 450-2009), defined active packaging and packaging materials as deliberately implemented components that would release or adsorb substances into or from the packed food or the environment surrounding the food. In this way, chemical compounds that adversely affect the packaged food (e.g., excessive humidity, ethylene, oxygen) are removed from the food or its environment, and substances that have a beneficial effect are introduced into the product or its environment (e.g., carbon dioxide, antimicrobial substances) (Carvalho et al., 2021). Active packaging systems influence mainly the rate of respiration (especially raw products from plant origin), reduce the growth of microorganisms, and limit oxidation or moisture migration (Kuswandi & Jumina, 2020). Application of active packaging systems could reduce the amount of necessary preservatives in food, and may eliminate or enhance another process used to prolong the food shelf life (e.g., modified atmosphere packaging) (Firouz et al., 2021).

A promising direction for the development of active packaging is the application of biodegradable compounds and bio-preservatives as well as nutraceuticals, antioxidants and antimicrobial agents of natural origin in packaging materials (Petkoska et al., 2021). Food product sustainability could also be supported by the replacement of fossil-based packaging materials with compounds obtained from natural sources (e.g., chitosan, starch, seaweed, animal proteins) and the development of bio-based films, which could be enriched with bioactive compounds such as essential oils, plant extracts, enzymes, chitosan and/or organic acids (Soro et al., 2021). This is in line with the global trend of developing environmentally friendly technologies and confirms that consumers tend to purchase sustainable alternatives over non-sustainable (Granato et al., 2022). A lot of active packaging is being developed in research laboratories, and a large part of them is available on the market—from simple moisture-adsorbent pads to complex systems for the absorption or emission of specific chemical compounds (Firouz et al., 2021). Recognisable active packaging systems applicable in the food supply chain are, for example, oxygen scavengers like Ageless® sachets (Mitsubishi Gas Chemical Co), Fresh-R-Pax® moisture absorbent trays (Multisorb Technologies Inc.), carbon dioxide emitter Fresh Pax type M (Multisorb Technologies Inc.) and antimicrobial agent Zeomic™ (Sinanen Zeomic).

4.4.2. Intelligent packaging solutions supporting reduction of food waste

Sustainable food production and distribution aims at providing the required amount of food products for local consumers (reducing unnecessary transport) as well as sufficient food supply for global recipients (e.g., in areas affected by famine). In both cases, food waste is an undesirable phenomenon (Ganeson et al., 2023). Unfortunately, according to FAO reports, over 30% of food produced for human consumption is lost or wasted (FAO, 2019). During the storage and distribution stages, it could be exposed to different harmful factors such as microbiological infection, violation of packaging integrity, temperature, and/or humidity other than optimal. Protection against the above factors is provided by various types of conventional packaging, while the need to monitor them in real-time has contributed to the development of intelligent packaging (Siracusa & Lotti, 2019).

The definition of intelligent packaging (Regulation (EC) No 450-2009) reveals the purpose of its development, according to which it is tasked with continuous control of food package conditions and the environment surrounding the food during storage and transport.

In general, the construction of intelligent packaging systems is based on an indicator or sensor that reacts specifically to defined phenomena such as the temperature change (e.g., time-temperature indicators), presence of recognisable chemical compounds (e.g., packaging integrity indicators) or microbiological contamination (e.g., freshness indicators) (Soro et al., 2021). Simple colorimetric indicators are the most user-friendly intelligent packaging solution because a change in their appearance can be easily recognised, signalling the presence of a monitored event, e.g., exceeding the limit temperature or occurrence of target chemical compounds (Schaefer & Cheung, 2018). Simple time-temperature indicators (TTIs) based on temperature-dependent chemical reactions, enzymatic activity or physical phenomena are also very applicable. Among some well-known representatives of this group are commercially available 3M™ Monitor Mark™ (3M Company), On Vu™ (Freshpoint) and Fresh Check® (Temptime Co).

More detailed information about the current state of packaged food products could be provided by integrity or freshness indicators, which are sensitive to specific volatile chemical compounds (Tichoniuk et al., 2021). Integrity indicators could detect gas from packed products or leaky packaging. Ageless Eye® (Mitsubishi Gas Chemical)—an integrity indicator—is one of the commonly used intelligent packaging elements, which are sensitive to the increase of oxygen concentration. It reacts positively in case of MAP packaging leakage (the loss of barrier against ambient oxygen), but it often has to be supported with some oxygen scavenger inside the packaging to avoid a false positive response because of residual oxygen released from the packed product (Schaefer & Cheung, 2018). Freshness (or ripeness) indicators are sensitive to different types of metabolites released into the packaging atmosphere during spoilage (or ripening) of packed food products (e.g., carbon dioxide, organic acids, esters, volatile sulphury or nitrogen compounds) (Kuswandi & Jumina, 2020). The simplest freshness indicators are based on the use of colorimetric markers sensitive to volatile substances that change the pH and colour of detection systems, and most often indicate the development of undesirable microflora associated with food product spoilage (Tichoniuk et al., 2021). Despite the many scientific reports on this type of indicators, they are relatively difficult to introduce into packaging systems on a larger scale due to difficulty with their integration (compatibility between materials, sizes, shapes, mechanisms of action), production costs (issues of mass production and indicator universality) and satisfactory analytical properties (specificity, sensitivity, detection limit, stability) (Sobhan et al., 2021). It is possible that the development of novel 3D printing technologies, such as stereolithography and extrusion-based 3D printing, will provide very precise and cost-effective tools for the fabrication of intelligent packaging (Tracey et al., 2022).

4.4.3. Novel automatic data collection (ADC) systems

Easily accessible and reliable information about the food product allows the supply chain participants to adjust the optimal packaging both in terms of its construction and materials, as well as following other properties required by the sustainable product. Specialised computer programs (connected with the IoT technologies) facilitate planning of the packaging needed to secure food products and optimise the arrangement of loads in means of transport or storage areas (e.g. as part of Warehouse Management System software) (Blanck, 2015). Labels and codes placed on the surface of the packaging, as well as electronic tags or chips placed in loads, allow for the automatic location of goods in the supply chains and protect them against product fraud and counterfeiting.

Radio Frequency Identification (RFID) systems are a kind of successor of automatic optical recognition technologies commonly used in ADC procedures because they offer a contactless transfer of information in real-time and possess a greater data storage capacity than traditional bar-codes (Bibi et al., 2017). RFID tags have various forms and are generally divided into groups of active, semi-passive and passive devices depending on their design. The transfer of data through the transmission of electromagnetic waves between RFID tags and receivers located in means of transport, elements of warehouse equipment and mobile devices helps to control the course of logistics processes, improves the flow of information about loads in the supply chain, and increases the possibility of tracking loads during transport and storage (Ahmed et al., 2018). RFID tags placed in primary or secondary food packaging, transportation containers or pallets allow for non-line-of-sign contact identification in the supply chain, which could significantly improve product traceability and inventory management. What is more, RFID tags in combination with sensors (temperature, humidity, volatile compounds, pH, integrity and traceability sensors) could strengthen the management of the food supply chain as well as indirectly influence the reduction of food waste and directly improve tools for food quality and safety control (Zuo et al., 2022).

Replacing RFID tags with NFC (Near Field Communication) labels allows ordinary consumers to read the deposited data using NFC-compatible smartphones. Additionally, chemoresponsive nanomaterials combined with NFC labels could estimate volatile chemical compounds in the packaging atmosphere (e.g., ammonia, water vapor) (Urbano et al., 2020). However, current consumers appreciate different types of labels included in a group of IoT solutions that extend the scope of information provided by the product packaging. QR (Quick Response) codes placed on food packaging surfaces can be scanned with a smartphone camera and redirect the consumer to websites containing a variety of product information (Khan et al., 2023). It can also be used for tracking the product throughout the supply chain, as well as for traceability in case of a recall (Trueqrcode, 2023). QR codes could provide consumers with additional information about sustainable practices used in the production of a given food item, such as organic farming, fair trade or non-GMO certifications. In addition, they can also educate in the area of responsible and sustainable consumption (also in connection with reduction of food and packaging waste). Using different types of IoT technologies and electronic information carriers on food packaging (RFID tags, NFC labels, QR codes) allows for the flexibility of updating the information connected with the product, without having to redesign the entire packaging (Zuo et al., 2022).

Conclusions

Products requiring packaging at various stages of production, distribution, and consumption attract special attention due to the need for their meticulous design. Packaging design is becoming more and more ingrained in industrial requirements, international standards, regulatory requirements, and best practices; it is no longer the sole purview of materials engineers. The goal of the new design methodology is to strike a balance between engineering, ecology, economics, and marketing. Reducing the harmful effects of packaging production and usage on the environment while preserving the highest level of food safety is the goal of the packaging industry revolution. The creation of food packaging is not as environmentally friendly as food losses resulting from improper packaging.

Packaging can also have a functional impact on the development of sustainable products and the promotion of sustainable food consumption. Active packaging systems equipped with absorbers of undesirable substances or releasing components that extend the shelf life of food increase its availability, stability, and possibility of consumption over a longer period. There is also scope for the introduction of biodegradable materials and/or components of natural origin that are more environmentally friendly. The impact of the environment on the packaged product and changes occurring in the food product can be continuously monitored by sensors and indicators that are the basis for the operation of intelligent packaging. Information about changes occurring in packaged food allows for effective control and reduction of food waste. More efficient management of food supply chains and easier transfer of information (also to the final consumer) is enabled by the development of modern systems for automatic data collection and augmented reality technologies related to packaging and labels.

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5. THE CIRCULAR ECONOMY IMPLEMENTATION IN THE FOOD SYSTEM—THE LIFE CYCLE PERSPECTIVE

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Abstract

The circular economy concept aims to create value for society and the economy while reducing environmental impacts. The circular economy is based on three principles driven by design—eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature. These principles can be applied to the food system, across all aspects of food design, from product concept, through ingredient selection and sourcing, to packaging. In order to assess the environmental load of any process or product in the food system, life cycle-based tools should be applied, since it can be beneficial and has potential for providing a holistic approach. This paper summarises the life cycle-based tools that have potential for complimenting the circular economy implementation in the food system. Based on that, the study identifies the current challenges as well as benefits and life cycle-based tools potential for providing a holistic approach that could strengthen available circular economy solutions.

Keywords: circular economy, life cycle assessment, sustainable product, food system.

JEL codes: F64, K32, N54, O13, O44, Q01, Q05.

Introduction

The circular economy (CE) concept is becoming more and more popular nowadays and is discussed widely in Europe and elsewhere. The reason for that is very simply—a shift from the linear economy, known as the "take-make-dispose" system, to the regenerative one seems to be necessary to protect the environment, reduce raw material dependence and boost innovation across different sectors of the economy (Chizaryfard et al., 2021; Kristensen & Mosgaard, 2020; Sánchez Levoso et al., 2020). The climate crisis also raises the need for taking rapid action aimed at improving the current state of the environment. The primary means of

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seeking to reach this aim should be achieving the Sustainable Development Goals (SDGs). The discussion about achieving the objectives of sustainable development set out in the Agenda 2030 shows that its implementation into practice is hard and has started to lose momentum (Paloviita & Järvelä, 2019) or has even begun calling sustainability "a theoretical dream" (Naudé, 2011) or living in the age of "sustainababble", which shows the profusion of using the word sustainable to mean anything environmentally better (Engelman, 2013). The CE concept is perceived as an approach relating to achieve local, national and global sustainability as well as operationalisation to implement the concept of sustainable development and achieve a sizeable number of SDG targets (Haupt & Hellweg, 2019; Kristensen & Mosgaard, 2020; Murray et al., 2017; Pauliuk, 2018; Schroeder et al., 2018; Suárez-Eiroa et al., 2019). The CE is focused on competitiveness and innovation, thus leading to corporate financial returns and further economic development (United Nations, 2015). In this perspective, the concept of CE has been recognised by the European Union (EU) as one of the biggest challenges.

5.1. Theoretical background of circular economy

In the literature, we may find a number of definitions of CE (Geissdoerfer et al., 2017; Kalmykovaa et al., 2018; Khan et al., 2022; Kirchherr et al., 2017). Although the theoretical foundations concerning the CE concept are not new, there is still no consensus in defining and conceptualising it (Homrich et al., 2018; Moraga et al., 2019). The most common description presents the CE as an "industrial system that is restorative or regenerative by intention and design" (Ellen MacArthur Foundation, 2013) or an economy "where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised" (European Commission, 2015). As mentioned before, the CE is a complete opposite to the linear approach. Following the CE concept organisations or businesses are focused on what happens to the product once it is thrown away. The assumption in the CE is that the availability of natural resources to manufacture the product is limited, and there is an important necessity to be concerned about the depletion of resources. The concept of quality associated with newness present in the linear economy is turned around (Stahel, 2016). There is a shift from the "cradle-to-grave" model, which is based on the take-make-consume-throw away pattern to the "grave-to-grave" one (McDonough & Braungart, 2010). When a product reaches the end of its life, its materials are kept within the economy, wherever possible and reasonable, and for as long as possible. It means that materials can be productively used again and again, in closed loops, for re-usage and creating further value. Such change in economic behaviour supports the CE movement and have a positive impact on its implementation. In practice, the CE focuses on reducing waste to a minimum as every product needs to be perceived as waste at the very beginning of its life (from the design phase).

The concept of CE is currently under ongoing discussion, especially concerning its definition and conceptualisation (Homrich et al., 2018; Korhonen et al., 2018; Moraga et al., 2019). It is also connected with an internal political agenda and regulations in this respect across Europe and in other developed countries (Ellen MacArthur Foundation, 2013; OECD, 2016; UNEP, 2011; World Economic Forum, 2023). As a consequence of the continuous and sustained efforts to adopt to the green economy and green growth concepts, the CE is still interpreted differently depending on the role and specific interests or priorities of stakeholders (Corona et al., 2019; Hartley et al., 2020; Jabbour et al., 2020; Kirchherr et al., 2017; Mayer et al., 2019; Valls-Val et al., 2000).

5.2. Circular economy principles

At the very beginning of the CE concept, there were only three principles—sharing, leasing and reusing. Nowadays various principles have been used in academia as well as by practitioners. They are listed in Table 5.1.

Table 5.1. Circular economy principles

Description		Source
R-principles		
3Rs	Reduce, Reuse, Recycle	Lieder & Rashid, 2016
4Rs	Reduce, Reuse, Recycle, Recover	Kirchherr et al., 2017
5Rs	Rethink, Reduce, Reuse, Recycle, Repair	Li, 2011
6Rs	Reduce, Reuse, Recycle, Recover, Remanufacture, Redesign	Yan & Feng, 2014
7Rs	Reduce, Reuse, Recycle, Recover, Rethink, Resilient, Regulate	Xing et al., 2017
8Rs	Rethink, Redesign, Reduce, Reuse, Return, Repair, Recycle/recover, Refuse	Maia et al., 2019
9Rs	Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	van Buren et al., 2016
10Rs	Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Potting et al., 2017
Other CE principles		
3 CE principles defined by the Ellen MacArthur Foundation	1) Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows, 2) Optimise resource yields by circulating products, components and materials in use at the highest utility at all times in both technical and biological cycles, 3) Foster system effectiveness by revealing and designing out negative externalities	Ellen MacArthur Foundation, 2015

Table 5.1 – cont.

Description		Source
6 CE principles defined by the Circular Economy Standard BS 8001:2017	1) System thinking, 2) Stewardship, 3) Transparency, 4) Collaboration, 5) Innovation, 6) Value optimisation	BSI, 2017
6 CE principles defined by Ghisellini et al.	1) Reduction, 2) Reuse, 3) Recycle, 4) Appropriate design, 5) Reclassification of materials into technical and nutrients, 6) Renewability	Ghisellini et al., 2016
7 operational principles of CE defined by Suárez-Eiroa et al.	1) Adjusting inputs to the system to regeneration rates, 2) Adjusting outputs from the system to absorption rates, 3) Closing the system, 4) Maintaining the value of resources within the system, 5) Reducing the system's size, 6) Designing for CE, and 7) Educating for CE	Suárez-Eiroa et al., 2019
3 CE principles defined by Bocken et al.	1) Narrowing loops, 2) Slowing loops, 3) Closing loops	Bocken et al., 2016

Source: adopted from (Papageorgiou et al., 2021).

In general, there are two types of core principles. One type relates to the R frameworks, and the other (other CE principles) focuses on the system's perspective, which states that the CE requires a fundamental shift instead of incremental twisting of the current system (Kirchherr et al., 2017). The first mentioned group of principles, the R frameworks, is perceived by many authors as the core principles of the CE, due to its "how-to" approach (Reh, 2013; L. Zhu et al., 2010; Q. Zhu et al., 2010). Moreover, the 3R framework is the basic and the very first approach to the CE and the 4R framework is the core of the European Union Waste Framework Directive (European Commission, 2008), which introduces an additional "R"—"recover", as the fourth principle.

Other R frameworks beyond the 3R and 4R frameworks, such as the 9Rs (van Buren et al., 2016) or even 10Rs (Potting et al., 2017) have been proposed. All types of the R framework share a hierarchy and shift from the linear economy to the circular one, where "recover" is nearest to the linear economy, but "refuse"—to the circular one. The first R, "recover" is the situation where the incineration of material with energy recovery takes place. The closest to the circular economy concept is to "refuse", where the product becomes redundant by abandoning its function or by offering the same function with a radically different product (Potting et al., 2017).

5.3. The circular economy in the food system

Implementation of the CE principles is among the priorities of the European Union reflected in the undertaken activities and related to the very basis of the consumer policy and legislative strategy employed by the Commission. The benefits associated with adopting the CE practices are increasingly perceived as an important and inherent factor of economic growth in both regional and national economic sectors (Ellen MacArthur Foundation, 2020; Patwa et al., 2021). Thus, this concept is increasingly being adopted by the current norms and standards. In March 2020, the European Commission adopted a new circular economy action plan focused on the seven sectors that use most resources and where the potential for circularity is high. One of the listed key product value chains is food, water and nutrients. As the model of production and consumption that incorporates the CE principles involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible (European Commission, 2020), the CE for food is close to natural systems of regeneration. In this concept, organic resources such as food by-products are clean and free from contaminants, which enables their return to the loop in different formats. In the food system, the most important rule of the CE is prevention and redistribution, as showed in Figure 5.1.

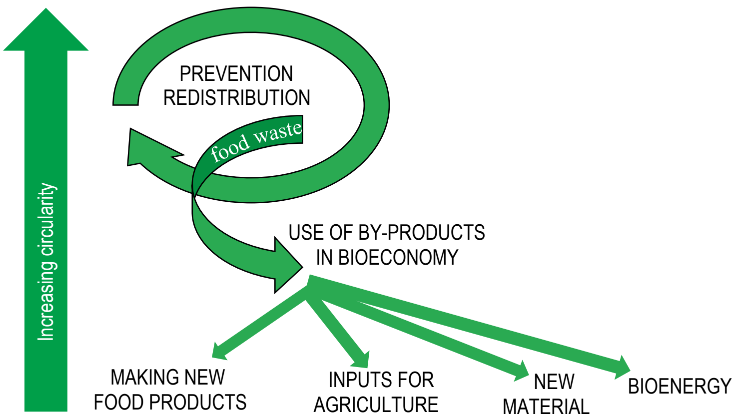

Figure 5.1. Principles of food system in circular economy
Source: on the basis at (Ellen MacArthur Foundation, 2019).

Prevention aims at tracking food waste and providing information in order to prevent edible food waste. It also covers the design phase, where food products are designed according to the latest eco-design trends. Prevention also includes the information phase, where all interested parties are informed about how to avoid food wastage. Redistribution aims to eliminate food waste. There are many ways of doing it, including serving meals as redistributed food to the needy. Food by-products generated at several stages of production can be used in the chain for different purposes, such as creating new products, producing new materials, such as fabrics for the fashion industry, inputs for agriculture (e.g. fertilisers) or as potential sources of bioenergy.

5.4. Circular economy in a life cycle perspective for the food sector

The importance of introducing the CE strategies in the food sector is very high. The food value chain is one of the main contributors to pollution worldwide and is responsible for significant resource and environmental pressures. Furthermore, it is currently estimated that about 20% of the total food produced is lost or wasted in the EU (European Commission, 2020). Additionally, on the one hand, there is exponential growth of total demand for food, feed and fibres, but on the other one, a relentless decline of arable land is observed (European Environment Agency, 2020). Moreover, in the food sector, direct or indirect interdependencies are very commonly observed in terms of resource competition for food or bioenergy, food loses and wastage and as consequence, which impacts the whole value supply chain. There are ten sustainability principles that affect the food value chain development, which are presented in Figure 5.2.

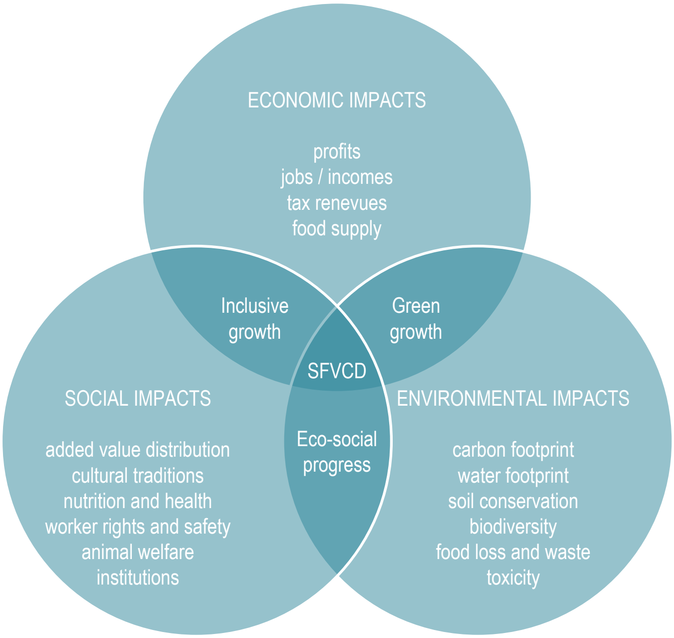

Figure 5.2. Sustainability principles of food value chain development
Source: adopted from (Neven, 2014).

These principles are a good path to present performance from the perspective of the triple bottom line: economic, social and environmental sustainability. The important thing is that all these three dimensions shall be treated together as they overlap, and only together give the complete picture of the state of the art.

There are a lot of pathways for improving the resource efficiency of food system activities. The application of the CE principles can encourage technical innovations for ensuring a more sustainable use of renewable resources and reduce environmental damages as well as depletion of non-renewable resources. Another important thing is assessing the environmental impacts of new circular strategies. For that purpose, the implementation of the Life Cycle Assessment (LCA) methodology can be useful (Ingemarsdotter & Dumont, 2022). This worldwide known tool used in environmental management allows us to assess the environmental impacts generated by an individual process of reuse, recycling or recovery of wastes or by-products. LCA makes it possible to identify and quantify environmental loads, as well as evaluate their potential environmental impacts and assess opportunities for their reduction. However, introducing LCA as a process of evaluating the environmental impact of the assessed product over the entire life cycle does not allow for assessing the effects in terms of circularity, both concerning the product that has generated waste and by-products as well as the product that will use them to work out new products (Rocchi et al., 2021; Silvestri et al., 2022; Stillitano et al., 2022). The solution for introducing the sustainability aspects may be to match the life cycle of the product whose circularity will be assessed with the life cycle of the product whose environmental impacts will be assessed, integrating circular strategies within system boundaries (Falcone et al., 2022). It is equally important to note that the sustainability aspects cover three spheres of environmental, economic and social impacts. It can be assessed in associated analysis including, respectively, the environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and social Life Cycle Assessment (S-LCA). The rules for providing such analysis are standardised and present in the current ISO 14000 standards series. Following the rules, the sustainable LCA analysis can support the evaluation of environmental, economic and social impacts of products or service systems or even (re)designing it. The obtained results do not provide information about the circularity aspects of the assessed product or service. This gap can be filled by using additionally the circularity indicators, which can measure the circularity of resources and material flows in LCA studies (Ingemarsdotter & Dumont, 2022; Stillitano et al., 2021). Two indicators are well-known and useful for this purpose. They are the Material Circularity Indicator (MCI), created and popularised by the Ellen MacArthur Foundation, and the Circular Transition Indicators (CTI) developed by the World Business Council for Sustainable Development (WBCSD). The former, MCI, measures which linear flow has been minimised and which restorative flow has been maximised, while considering the product's lifetime and intensity of use. It focuses on the flow of materials throughout the manufacture and use of the product and allows for including and introducing the use of recycled or reused materials as well as extending product life. The latter, i.e. CTI, allows for assessing material flows within company boundaries. The goal is to minimise resource extraction and waste material at three key intervention points: inflow, outflow—recovery potential, and outflow—actual recovery. All of them can be measured with specific indicators and the results can help with closing and optimising the loops, and this way helping to assess the circularity of products or services.

Nowadays there are attempts to assess circularity in the food supply system using Life Cycle Assessment (Nikkah et al., 2021; Papageorgiou et al., 2021). However, the life cycle tools have their limitations, which include: time intensive data collecting and gathering, missing impact data or models for LCA, data uncertainty, dependency on other tools for decision making, and allocation of ecological burdens among co-products (Curran, 2014). Moreover, it can be assessed that the development of CE indicators in the food sector is currently in a premature stage. There are many important open questions to answer. Particularly relevant issues are how to match the material efficiency approach with the systemic approach and where to put the boundaries of processes for defining indicators (Vermeyen et al., 2021).

Thus, there is a real need to provide future research in the field and to introduce specific circularity indicators, which can help to overcome important methodological and practical barriers.

Conclusions

Due to their relative novelty and dynamic changes occurring in the issues raised, there is a need for a standardised indicator-based framework that could be applied for measuring circularity in the food sector. Nevertheless, further research is needed to determine the right way of assessing circularity. Although the life cycle tools are very good for assessing it, future research should focus on developing and introducing a common framework. The present study is an additional voice in that discussion and can be useful as a starting point for further research in this area. It indicates the strengths and weaknesses of existing solutions and tools, which can be helpful in assessing circularity. Bringing the CE into practice and the economy is important, but we cannot forget about monitoring its progress influencing the rate of sustainable economic growth. In this context, further research should focus on identifying, improving and developing CE indicators that will reflect on all three dimensions and aspects of sustainable development. It is crucial to focus not only on the environmental aspects but also on the social, economic and governance aspects. Putting all these assumptions together is a challenge, but such an approach will allow us to ensure that the framework includes indicators able to capture aspects that are relevant to all pillars of sustainable development.

More practical research in the field of measuring circularity of different food sectors is also needed to provide empirical findings coming from different case studies and can be useful for application in the identified framework. The circularity of the food sector is one of the key areas that we need to focus on when improving its sustainability. In this context, there is an increasing need for introducing proper tools to measure and monitor progress towards the CE. Indicator-based frameworks seem to be a proper way to both measure and monitor progress towards the CE in the food sector. A systemic perspective of such activities is needed to capture the multiple dimensions and complexity of the transition towards the CE.

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6. SUSTAINABLE MANAGEMENT OF FRUIT WASTE PRODUCTION

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Abstract

The main goal of this paper is to review sustainable strategies presented in the literature for managing fruit processing by-products according to the circular economy, which could be useful for companies. In the food processing of fruits, the waste can be utilised directly or indirectly. The direct utilisation of fruit waste does not ensure full valorisation and does not fully minimise the environmental impact. The most sustainable management for the full valorisation of fruit waste according to the circular economy is the indirect utilisation, which requires an energy-intensive drying process before the biorefinery approach. Sustainable Development Goal (SDG) 12.3 promotes the reduction of food waste and food loss throughout the supply chain to achieve sustainable development by 2030, especially at retail and consumption levels. The fruit processing industry produces large amounts of by-products, mainly removed by landfilling or incineration. However, these methods cause emissions of carbon dioxide, methane and ammonia, and release dioxin into the environment. In addition, it causes a loss of valuable biomass and nutrients and an economic loss. The sustainable management of fruit processing by-products is important to reduce the amount of food waste deposited in landfills and to develop strategies through their reuse for full valorisation and added economic value. The currently proposed biorefinery only focuses on partial valorisation of fruit waste, which is not completely compatible with the closed-loop economy framework and economically feasible due to the low-efficiency bioprocesses. Therefore, there is a need for sustainable conception in the biorefinery approach, which can provide full valorisation of fruit waste according to the circular economy.

Keywords: fruit by-products, sustainable strategies, management of by-products, circular economy.

JEL codes: Q01, Q16, Q42, Q53, Q55, Q56.

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Introduction

The global production of fruit waste only generated by the processing industry is estimated at more than 190 million tons per year (FAOSTAT database). Currently, fruit waste management has an impact on the environment and is not in agreement with the circular economy because it is landfilled in composting plants or fed into the fermentation process of biogas plants. However, these methods cause greenhouse emissions and release waste into the environment. In addition, it causes a loss of valuable biomass, nutrients and an economic loss.

In the literature, there are many sustainable strategies for the valorisation of fruit waste mainly under a biorefinery approach to produce bio-products, biofuels, biofertilizers and bioenergy (Pathak et al., 2016; F. Zhang et al., 2021). The purpose of a biorefinery system is to minimise the impact on the environment by reducing fruit waste volumes accumulated in landfills and the use of closed-loop economy processes. However, currently, the proposed biorefinery only focuses on partial valorisation of fruit waste, which is not completely compatible with the closed-loop economy framework and is not economically feasible due to the low-efficiency bioprocesses. Therefore, there is a need for sustainable conception in the biorefinery approach, which can provide a full valorisation of fruit waste according to the circular economy. Only biorefinery in the closed-loop technology is a promising way to enhance economic efficiency and decrease the environmental influence according to sustainable development.

In this context, this review analyses the sustainable management of fruit processing by-products in a biorefinery approach to achieve their full valorisation according to the circular economy. Additional complete valorisation is discussed in five main stages, namely: pretreatment, extraction, dark or aerobic fermentation, anaerobic digestion and posttreatment.

6.1. Economic determinants of fruit waste production in Poland

The food sector is one of the most important and fastest-growing branches of the Polish economy. Poland is one of the largest fruit producers in Europe. In 2021, it was third behind Spain and Italy. In 2022, more than 5.28 million tons of fruit were produced in Poland, with apples, berries and cherries having the largest share (Table 6.1). Apples constituted by far the largest proportion of all fruit produced in Poland in the last 5 years (79.13%). Berries harvest in Poland accounted for 11.49% of all fruit production in Poland during the analysed period (Nosecka, 2022).

Table 6.1. Fruit production in Poland in 2018–2022

Specification	Harvest (in thousand tons)					Harvest structure (average value 2018–2022) (%)
	2018	2019	2020	2021	2022	
Fruits—total	5072.5	3938.0	4518.4	5059.5	5282.5	
Apples	3999.5	3080.6	3555.2	4067.4	4200.0	79.13
Strawberries	195.6	177.0	146.0	155.9	180.0	3.61
Sour cherries	200.6	151.9	155.5	166.6	183.0	3.60
Currants	164.6	126.2	145.9	152.0	142.0	3.07
Plums	121.1	95.0	111.7	117.4	132.0	2.42
Raspberries	115.6	75.7	123.2	103.9	105.0	2.19
Pears	90.9	67.6	61.0	68.6	80.0	1.55
Cherries	60.0	44.4	51.3	59.1	77.0	1.21
Chokeberries	50.2	40.8	66.1	66.0	55.0	1.17
Highbush blueberries	25.3	34.8	55.3	55.3	64.0	0.98
Other berries	8.3	6.8	16.0	15.5	23.0	0.29
Gooseberries	11.5	9.6	9.6	9.8	10.0	0.21
Walnuts	8.5	5.2	7.0	6.8	11.0	0.16
Hazelnuts	6.6	5.4	7.7	7.6	9.5	0.15
Peaches	10.6	8.5	3.8	4.5	6.5	0.14
Apricots	3.6	3.1	3.1	3.1	4.5	0.07

Source: (Nosecka, 2022).

The fruit industry processes fruit mostly into concentrated juices, frozen fruit, fruit concentrates and jams. The preserve production forecast was to reach 1.17 million tons in 2022/2023, up from 1.13 in the previous year. The total production of concentrated juices, nectars and beverages was to reach 2.23 million tons (compared to 2.27 million tons in the previous year). In the 2021/2022 season, 83.9% of apples, 32.9% of strawberries, 28.7% of raspberries and 47.6% of currants were allocated to the processing of concentrated juices. A similar structure of fruit allocation was forecast for the 2022/2023 season (Nosecka, 2022).

Generally, fruit waste can be generated at two stages: fruit processing and food processing (Figure 6.1).

During the fruit preparation process, waste takes the form of leaves, fruit stems and spoiled, damaged fruit, which is about 0.5% of the fruit weight (Lipiński et al., 2018). However, in the case of food processing, waste is generated mainly in the form of pomace, peels, cores, seeds and tails, which amounts to 20%–60% of the fruit weight, depending on the fruit and technological process (Bayram et al., 2021; Lau et al., 2021).

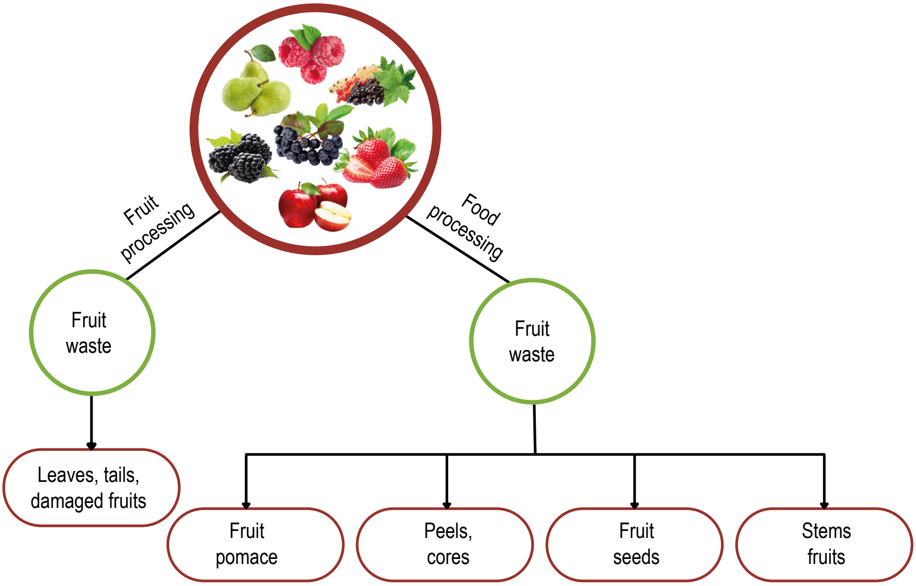

Figure 6.1. Stages of fruit waste production
Source: own compilation.

6.2. Fruit waste composition

Fruit waste is well known for its high content of bioactive compounds with antioxidant and antimicrobial properties such as flavonoids, tannins and phenolic acids. Especially, fruit pomace contains a high content of bioactive substances, reaching up to 80% of their total content in fruit (Cubero-Cardoso et al., 2020; Ovcharova et al., 2016; Reguengo et al., 2022; Reynoso-Camacho et al., 2021; Tian et al., 2018). Figure 6.2 shows the general structure of the phytochemicals contained in fruit by-products.

Due to its high polysaccharide content, the presence of mono-, di- and oligosaccharides, as well as citric and malic acid, apple pomace is considered to be a potential source for the extraction of value-added compounds such as simple sugars like glucose, fructose, and sucrose. It is also a rich source of carbohydrates, pectin, crude fibre, proteins, vitamins and minerals and, as such, is a good source of nutrients worth recovering (O'Shea et al., 2015). Furthermore, residues from the production of blueberry juice are also a valuable source of health-promoting compounds. Berry pomace has a high concentration of anthocyanins and polyphenols. It also comprises modest quantities of hydroxycinnamic acids (Kylli, 2011; Maatta-Riihinen et al., 2004). However, the highest contents for p-coumaric acid, chlorogenic acid and caffeic acid are found in blueberries, chokeberries, highbush

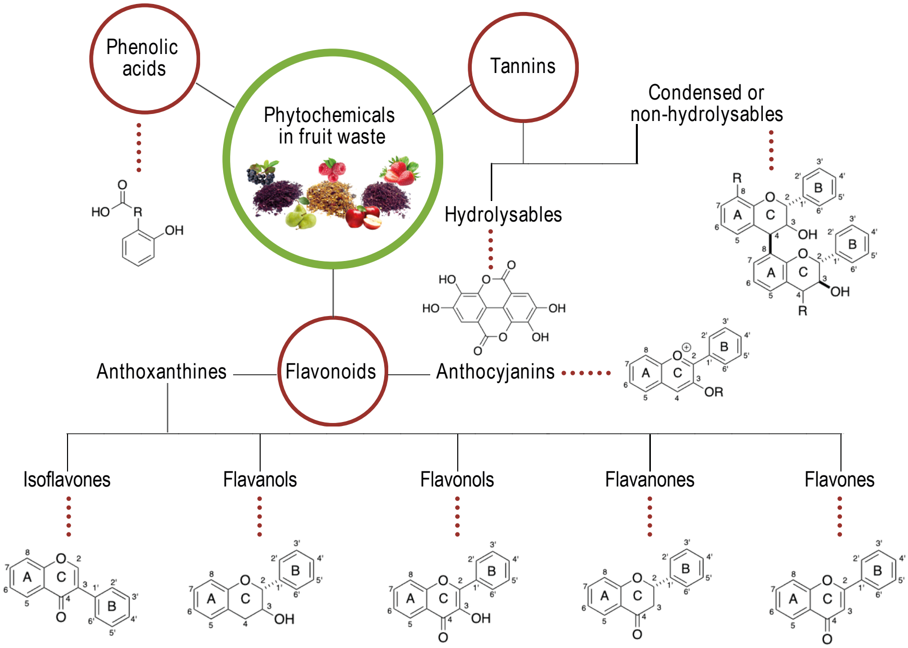

Figure 6.2. General structure of phytochemicals contained in fruit by-products
Source: own compilation.

blueberries, American cranberries, blackcurrants and lingonberries, which have the highest levels of flavonoids, particularly aglycones and derivatives of quercetin and myricetin (Häkkinen et al., 1999; Koponen et al., 2007; Kylli, 2011; Maatta-Riihinen et al., 2004).

6.3. Directions in fruit waste production

Recently, what seems to be an emerging issue is finding an integrated technology for fruit waste recycling, resource recovery and the production of high-value products under the circular economy scheme with a minimal environmental impact (Borujeni, Karimi et al., 2022; Costa et al., 2022; Górnaś et al., 2016; Mirabella et al., 2014). In the case of food processing of fruit, the waste can be utilised directly or indirectly (Figure 6.3).

In the direct utilisation of fruit, waste can be landfilled in composting plants or can be subjected to aerobic or anaerobic fermentation (Figure 6.4). This way of fruit waste management can be used when the microbial quality of the fruit waste is low. During the aerobic fermentation compost is formed which is used as organic fertiliser. However, better valorisation can be achieved by the anaerobic digestion, which leads to the production of biogas and post-fermentation waste, which in

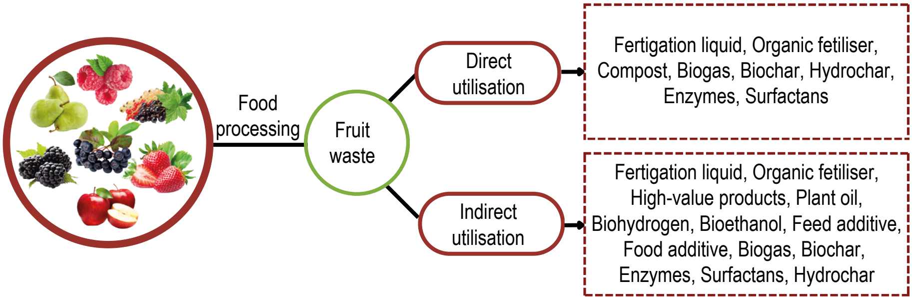

Figure 6.3. Strategies to use fruit waste after food processing
Source: own compilation.

turn can be transferred to biochar or harmless organic fertiliser and fertigation liquid. However, the direct utilisation of fruit waste results in the loss of bioactive substances contained in them. What is more, greenhouse gases are emitted during composting. It means that this management method does not ensure full valorisation of fruit waste and does not fully minimise the environmental impact.

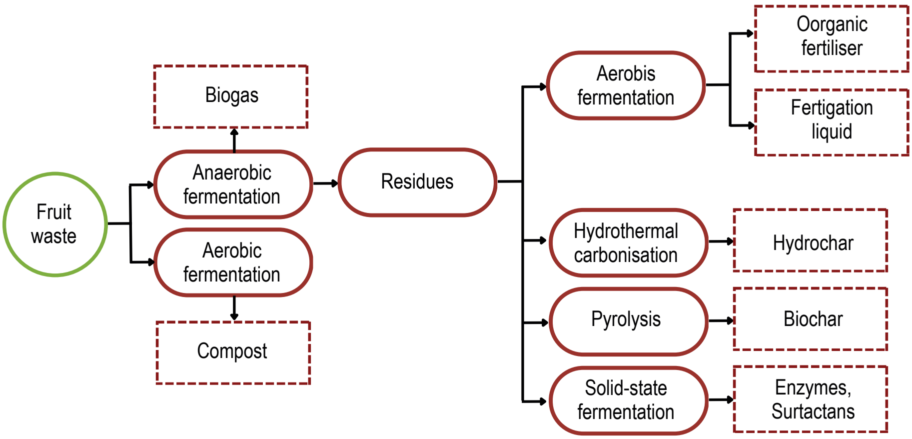

Figure 6.4. Direct utilisation of fruit waste after food processing
Source: own compilation.

On the other hand, the indirect utilisation is the most sustainable strategy for the full valorisation of fruit waste according to the circular economy. At the beginning, the fruit waste is subjected to a drying process and then to further stages of biorefining, such as:

- the process of extraction,
- dark fermentation,
- aerobic fermentation,
- anaerobic fermentation (Figure 6.5).

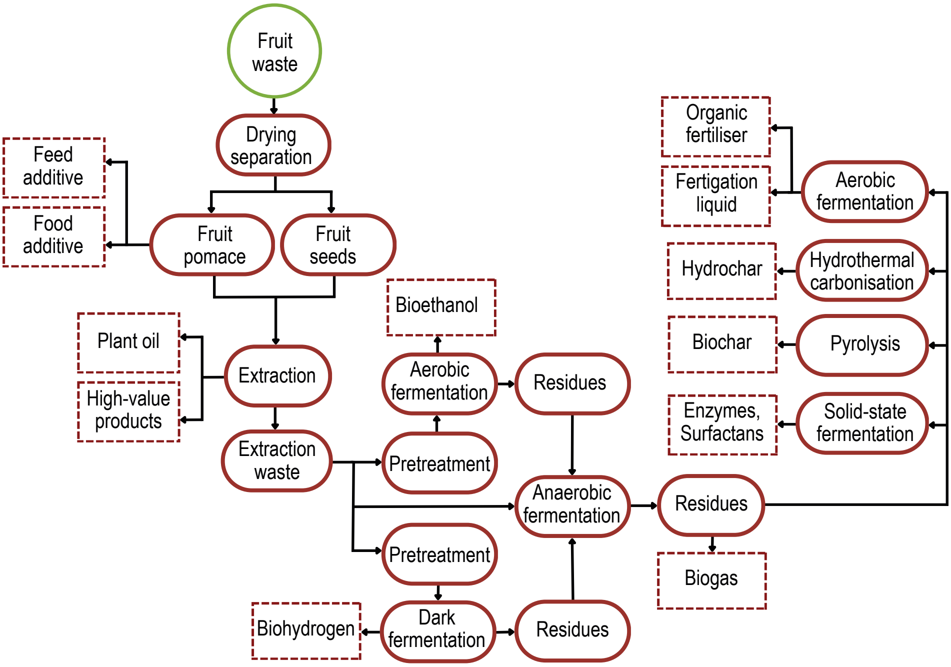

Figure 6.5. Indirect utilisation of fruit waste after food processing
Source: own compilation.

6.3.1. Drying process

After the production of juices and smoothies, fruit waste contains large amounts of water (about 70%) that must be removed to ensure its microbiological stability (to about 5%). Currently, several drying methods are being investigated for fruit pomace (Radojčin et al., 2021). From a practical point of view, the most often applied drying techniques are forced air and freeze-drying methods. The biggest concern with drying is that the bioactive compounds in fruit by-products are sensitive to heat and oxygen. Several studies have evaluated the effects of different drying methods on the degradation of bioactive compounds from fruit pomace (Vashisth et al., 2011). The freeze-drying method guarantees the best quality of the obtained dried pomace. However, it is not very widely used due to the long water removal time, which is associated with high-energy consumption. Therefore, other methods such as sun or hot air drying are applied in the industry. For full valorisation of fruit pomace, it is critical to define drying conditions that can maximise the retention of bioactive compounds while remaining economically feasible on a larger industrial scale.

6.3.2. Extraction process

Depending on the quality parameters, dried fruit pomace can either be used directly as food and feed additives (Nawirska, 2005) or can be ground, and then fruit seeds can be separated from the fruit pomace powder. The fruit seeds can be used for oil extraction with mechanical or chemical methods. The fruit pomace without seeds can be subjected to an extraction process to recover bioactive compounds, e.g., pectin, anthocyanins, polyphenols, and proanthocyanidins. The recovered natural bioactive substances can be used in the food, pharmaceutical or cosmetic industries. These substances can be extracted using conventional or non-conventional techniques. The conventional extraction techniques include maceration and Soxhlet extraction, which requires a large volume of solvent and heat, making these methods time and energy-consuming (Rodriguez & Raghavan, 2021; Q. Zhang et al., 2018). Apart from that, they are less suitable for heat-sensitive ingredients. To overcome the disadvantages of these techniques, there are other extraction methods, such as unconventional or green extraction, that exhibit shorter extraction times, high yield and selectivity as well as lower solvent consumption (Azmir et al., 2013; Chemat et al., 2012). Among the examples of these techniques are ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, enzyme-assisted extraction and pulsed electric field extraction (Sagar et al., 2018). They can improve the extraction of heat-sensitive bioactive ingredients due to lower processing temperatures. To fully utilise fruit by-products, it is critical to optimise extraction methods and conditions that can maximise the recovery of bioactive compounds while remaining economically feasible on a larger industrial scale (Tao et al., 2014).

The extraction residue can be directly transferred to anaerobic digestion or it can go through the pretreatment process before dark or aerobic fermentation. Pretreatment with enzymes, bases, inorganic acids or physical techniques is required to hydrolyse non-fermentable sugars.

6.3.3. Dark fermentation (DF)

Among all biohydrogen production technologies, DF is the most promising one due to the low energy input and lack of oxygen generation (Basak et al., 2020; Hay et al., 2013). In this process, fruit waste is converted to a mixed gas containing H_2, CO_2, H_2S, CO and CH_4, organic acids and alcohols using anaerobic bacteria (*Clostridium*, *Enterobacter* and *Bacillus*) in the absence of light and oxygen (Table 6.2).

Until now, the maximum yield of hydrogen production through the DF process is 4 moles of H_2 per hexose molecule, which is equal to 33% (on sugars). Apart

Table 6.2. Apple waste as substrate for bio-H_2 production in DF

Substrate	Microorganisms	Pretreatment	Bio-H_2 production [mL/g TS*]	Reference
Apple peel	microbial consortium	not applied H_2SO_4 solution NH_3 liquor	41.28 76.68 101.08	Feng et al., 2010
Apple pomace	rice rhizosphere microflora	not applied	90	Doi et al., 2010

* TS – total solids.

Source: own elaboration.

from that, hydrogen production through DF leads to a negative net energy balance (Martinez-Merino et al., 2013). Therefore, in order to increase the hydrogen yield production, residue in the form of organic acids/alcohols is utilised in anaerobic digestion to provide biomethane (Redwood et al., 2009).

Many studies have focused especially on the production of bio-H_2 from food waste, while there are only a few studies investigating the production of bio-H_2 from fruit by-products. Feng et al. (2010) have examined acid and base pretreatment of apple peels to produce bio-H_2 with river sludge. On the other hand, Hwang et al. (2011) have not applied any pretreatment processes. In fact, they studied a two-stage fermentation system (dark/dark) with sewage sludge fed with different ripened fruit feedstocks. In the two-stage system, the energy efficiency (H_2 conversion) obtained from mixed fruit waste increased from 4.6% (in the first stage) to 15.5% (in the second stage), which indicated the energy efficiency can be improved by the combined H_2 production process.

6.3.4. Aerobic fermentation (AF)

Fruit pomace, or the extraction residue, consists of fermentable sugars and insoluble polysaccharides and therefore can be converted into bioethanol or biobutanol by alcoholic or acetone-butanol-ethanol fermentation. Production of these biocompounds required the following three steps: pretreatment, hydrolysis and sugar fermentation processes. The aim of the pretreatment is to prevent lignin against substrate degradation and inhibitors, which leads to an increase in ethanol production efficiency. The most commonly used pretreatment methods are mechanical and physicochemical processes such as milling, steam explosion, griding and acidic, alkalic or organosolv heating (Table 6.3).

In the second step of bioethanol production, enzyme hydrolysis or acid hydrolysis is applied to form fermentable sugars from fruit pomace, which consists of cellulose, hemicellulose, pectin and lignin. To overcome the problem with pectin and lignin, high enzyme loadings, such as pectinase, cellulase and glucosidase, are required, where the high cost of applied enzymes influences the economic

Table 6.3. Apple pomace as a substrate for bioethanol production

Substrate	Pretreatment	Enzymes	Microorganism	Ethanol production	Reference
Apple pomace	acidic heating	cellulase	*S. cerevisiae*	1.10 g/L-h	Demiray et al., 2021
Apple pomace	alkalic heating	pectinase cellulase hemicellulase	*S. cerevisiae*	1.5 g/L-h	Magyar et al., 2016
Apple pomace	acidic treatment	pectinase cellulase hemicellulase	*S. cerevisiae*	190 g/kg	Parmar & Rupasinghe, 2013
Apple pomace	ethanol treatment	pectinase cellulase hemicellulase	*S. cerevisiae*	173.3 g/kg	Borujeni, Alavijeh et al., 2023

Source: own elaboration.

viability of ethanol production. Therefore, to decrease the cost of production, in-house enzymes were applied (Choi et al., 2015).

The last stage of bioethanol production is the fermentation process carried out mainly with industrial microorganisms such as *Saccharomyces cerevisiae.* Due to the high free sugar content in fruit pomace and less fermentation inhibitor formation, the productivity of bioethanol is much higher (1.1–4.7 g/L-h) than with lignocellulosic biomass (0.1–0.9 g/L-h) (Caldeira et al., 2020). It was reported that the maximum yield amounted to up to 190 g of ethanol per kg of apple pomace using an enzymatic pretreatment (Parmar & Rupasinghe, 2013).

Borujeni, Alavijeh et al. (2023) and Borujeni, Karimi et al. (2022) developed the conversion of apple pomace into bioethanol and bioproducts (pectin, chitin/chitosan, mycoproteins) by applying organosolv pretreatment (50% ethanol with 0.5 wt% acid, at 100°C) coupled with simultaneous saccharification and fermentation with fungi *Mucor indicus* (Figure 6.6).

Vaez et al. (2023) applied pretreatment of dried apple pomace with dilute sulfuric acid. Extraction of liquid fraction gave pectin and residues, which after AF produced bioethanol. Besides, the solid fraction after the pretreatment process was subjected to anaerobic fermentation to produce biogas. The highest yield for 1 ton of dried apple pomace was 164 kg of pectin, 99 L of bioethanol and 33.6 m^3 of biogas.

During AF and purification, waste is generated in the form of fermentation broths, stillage and residues after distillation. It consists of aqueous suspensions containing fruit solids, microorganisms and microbial debris. Currently, this waste is used as soil fertiliser with an impact on the environment (Mohana et al., 2009). However, the fermentation residues could also be used as feedstock in different bioprocesses to obtain other valuable products such as: biogas, surfactants or enzymes (Kharayat, 2012).

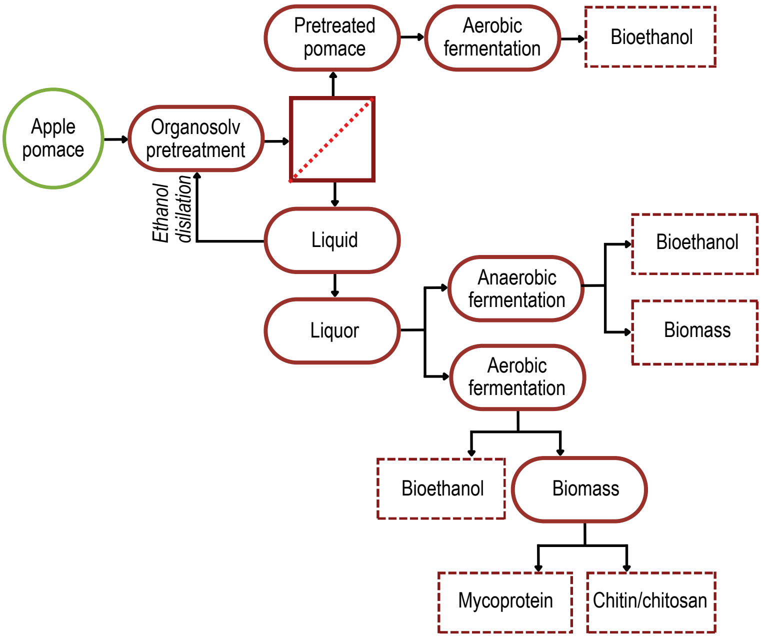

Figure 6.6. Conversion of apple pomace into bioethanol and bioproducts
Source: (Borujeni, Karimi et al., 2022).

6.3.5. Anaerobic fermentation (ANF)

ANF can be carried out from the remains of DF and the distillation process or directly after hydrolysation. The organic acids present in the fermented residue will be converted into biogas in the process of acetate- and methanogenesis. In the literature, there are some attempts to increase the energy efficiency of organic biomass by two-stage fermentation processes. Jung et al. (2022) have examined a two-stage system for the production of hydrogen and methane in mesophilic conditions from food waste. Chemical energy in feedstock was recovered up to 79% as renewable energy. In another study, the co-fermentation of garden/food waste was assessed in a two-stage process that combines hyperthermophilic DF and mesophilic ANF *(*Abreu et al., 2019*)*.

Biogas production by ANF is the most promising direction for the use of post-fermentation and distillation waste. However, due to the seasonal production of fruit waste, only co-digestion with another main feedstock can be used in commercial technology (Molinuevo-Salces et al., 2020).

Post-fermentation material is rich in nitrogen, phosphorus and organic matter and can be used as an organic fertiliser (Tambone et al., 2011) or as a soil conditioner (Tang et al., 2019). However, the digestate contains biodegradable organic residues and other contaminants. It could increase NH_3 emissions and induce environmental problems such as acidification and eutrophication (Rincon et al., 2019). Therefore, appropriate management of post-fermentation material is required before its safe discharge into the environment.

After separation, the liquid fraction (80–90% of the digestate total mass) rich in N and K can be used, e.g., for microalgae cultivation (Al-Mallahi & Ishii, 2022). The digestate solid (10–20% of the digestate total mass) is rich in C and P. There are some strategies to utilise it in value-added materials, such as: composting into biofertiliser (Du et al., 2018), pyrolysis in biochar (Kumar et al., 2021), hydrothermal carbonisation into hydrochar (Parmar & Ross, 2019) or solid-state fermentation into hydrolytic enzymes, biosurfactants and biopesticides (Cerda et al., 2019).

Conclusions

Sustainable management of fruit waste production is important to reduce the amount of food waste deposited in landfills and to develop strategies through their reuse for full valorisation and added economic value. According to the literature, fruit waste can be a good feedstock candidate for value-added chemicals and biofuel production in a biorefinery setting according to the circular economy.

In the food processing of fruit, depending on the quality of waste and the company's technological capabilities, the waste can be utilised directly or indirectly. The direct utilisation of fruit waste does not ensure full valorisation and does not fully minimise the environmental impact. The most sustainable management for the full valorisation of fruit waste, according to the circular economy, is the indirect utilisation, which requires an energy-intensive drying process before the biorefinery approach. However, there is still a long way to go for the cost-effective processes such as value-added phytochemicals extraction, biohydrogen and bioethanol production, which are in the early stages of research. Therefore, the above-presented biorefinery processes require a techno-economic analysis taking into account the type of biomass and its availability at the biorefinery site and throughout the production year.

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PART II
SUSTAINABLE CONSUMPTION

7. SUSTAINABLE HEALTHY DIETS

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Abstract

The main challenge of our time is, on the one hand, malnutrition or the increasing number of overweight and obese people, and on the other hand, degradation of the environment and natural resources as a result of production. There is an urgent need to promote well-balanced and safe diets that have a low negative impact on the environment, while being culturally acceptable and economically accessible to all. This chapter discusses the concept of a "sustainable healthy diet" in the context of international and national dietary guidelines as well as the environmental impact of production and consumption of selected food groups and types of dietary patterns.

Keywords: sustainable nutrition, dietary guideline, diet quality, environmental impact.

JEL codes: Q01, I12, I14.

Introduction

Over the last 200 years, there has been rapid growth in the world's population. It is estimated that the total population will reach eight billion in 2023, compared to one billion people in the early 19th century. Furthermore, the population is expected to grow steadily until 2060, when the number of people will reach over 10 billion (Statista, 2023). Still the same amount of natural resources must feed an ever-growing population, and it should be remembered that there are huge differences between countries and regions. The main challenge of the present times is, on the one hand, malnutrition or the increasing number of overweight and obese people, and on the other hand, degradation of the environment and natural resources caused by urbanisation and production, including food production. At present, food production and agriculture are the main causes of the global environmental

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change (Willett et al., 2019). It is reported that agriculture occupies approximately 40% of global land (Foley et al., 2005; Kirova et al., 2019). Food production is responsible for about 70% of freshwater use (Brauman et al., 2016; Mbow et al., 2019), and between 19% and 37% of global greenhouse gas emissions (GHGE) (Clark et al., 2020; Crippa et al., 2021; Mbow et al., 2019; Poore & Nemecek, 2018; Vermeulen et al., 2012).

The growth of the world's population and the extension of life is a huge challenge in the context of sustainable development aiming to secure the needs of future generations. To meet this challenge, countries around the world adopted the 2030 Agenda for Sustainable Development (United Nations 2030 Agenda) and its 17 Sustainable Development Goals (SDGs). SDGs are directly or indirectly related to nutrition, which should be not only healthy but also sustainable. The definition of sustainable diet was proposed by the experts during the International Scientific Symposium on "Biodiversity and Sustainable Diets—United Against Hunger" held on 3–5 November 2010 in Rome. This definition states that: "Sustainable diets are those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimising natural and human resources" (FAO, 2010). This definition indicates that the SHDs or sustainable nutrition patterns need to be nutrient-rich and safe, culturally acceptable, as well as low cost (affordable) and with low environmental impact. It affects various dimensions of sustainability (agricultural, nutritional, environmental, social, cultural and economic) and highlights the role of food consumption in contributing to the achievement of the SDGs, especially Goals 1 (No poverty), 2 (Zero hunger), 3 (Good health and well-being), 4 (Quality education), 8 (Decent work and economic growth), 12 (Responsible consumption and production) and 13 (Climate action) (FAO & WHO, 2019; Grosso, Mateo et al., 2020) (Table 7.1).

The definition of sustainable diet has provided a framework for discussion and actions on food system changes to implement the SHDs. Public health policy both at national and global levels requires a new vision of food systems and dietary guidelines considering the consequences of food production and under-, mal- and over-consumption for future generations and the planet. These actions include the following (FAO & WHO, 2019):

- providing affordable and desirable food for SHDs for the most vulnerable, considering the perspective of those who experience poverty and deprivation,
- promoting strategies for dietary behaviour change, including effective food and nutrition education,

Table 7.1. Link between main SHD indicators and SDGs

SHDs indicators	Explanation	Link to SDGs
Health aspects	1. Adequate nutrient intake ensures proper development and maintenance of health 2. Healthy nutrition reduces the risk of diet-related diseases such as obesity, cardiovascular diseases, cancer and other diseases 3. Malnutrition affects learning abilities 4. Awareness of SHDs affects better choice of food	(3) Good health and well-being (4) Quality education (6) Clean water and sanitation (12) Responsible consumption and production
Environmental aspects	1. Limitation of meat production and industrial agriculture (based on chemical use) protects environment and biodiversity 2. SHDs reduce GHGE, soil and water contamination related to food production 3. Sustainable solutions in food production and consumption ensure that the nutritional needs of a growing population are met	(6) Clean water and sanitation (12) Responsible consumption and production (13) Climate action
Affordability, acceptability, economic and sociocultural aspects	1. Poverty limits access to adequate food intake and fulfilling nutritional recommendations; therefore, affordable healthy diets may reduce malnutrition 2. Access to industrial innovation and infrastructure to change food production to greener and safer for human health and the environment affects human and animal welfare 3. Consumption of local food may contribute to territorial development 4. Short supply chains can benefit either consumers (lower product cost) or producers (increased income)	(1) No poverty (2) Zero hunger (8) Decent work and economic growth (9) Industry, innovation and infrastructure

Source: own elaboration.

- identifying potential trade-offs to make SHDs accessible, affordable, safe and attractive to all,
- development of national dietary guidelines defining SHDs, taking into account social, cultural, economic, ecological and environmental considerations.

7.1. Nutritional versus environmental recommendations

Developing dietary guidelines is not an easy process, as it requires demonstrating the relationship between health and a specific nutrient included in a food or diet. Dietary recommendations have changed over the years, and the most current ones for adults according to the World Health Organization (WHO) include the following (FAO & WHO, 2019):

- Energy intake should balance energy expenditure.
- Total fat intake should be less than 30% of total energy requirements, with a shift from saturated fat consumption to unsaturated fats, and the elimination of industrial *trans* fats.

- Free sugars intake should be less than 10% (or even less than 5%) of total energy intake.
- Salt intake should be less than 5 g/day (iodized salt is recommended).
- Eating at least 400 g of fruits and vegetables a day.

These recommendations are especially important due to the fact that unhealthy diets, along with tobacco use, physical inactivity and harmful use of alcohol, are key factors of noncommunicable diseases (NCDs), including heart disease, stroke, cancer, diabetes and chronic lung disease. They are responsible for 74% of all deaths worldwide. Most deaths from NCDs occur in low- and middle-income countries. The epidemic of NCDs has enormous health and socio-economic impacts on individuals, families and communities, and its health care-related costs represent a huge burden for the healthcare system (WHO, 2023).

Various national food-based dietary guidelines (FBDG), including the Polish ones, have adopted the WHO recommendations, but these guidelines vary around the world. In 2019, the EAT-Lancet Commission published the Report on Healthy Diets from Sustainable Food Systems, which focuses on the concept of planetary health and how it relates to our food choices. The report highlights that the current global food system is unsustainable and poses a serious threat to both human health and the planet. It identifies the need for transformational changes in food production and consumption. This report primarily promotes a plant-based diet, with a significant emphasis on fruit, vegetables, whole grains, legumes and nuts. It recommends limiting consumption of animal-based foods, especially red meat, limiting sugar, and encourages a shift to more sustainable sources of protein.

Nutrition recommendations are usually presented in the form of the Healthy Food Pyramid or the so-called Double Pyramid (Figure 7.1). The Double Pyramid (DP) is a graphic illustration of the concept of a balanced diet, which combines two pyramids: the Healthy Food Pyramid and the Environmental Pyramid. The Healthy Pyramid represents the nutritional quality of food. It sorts food products into 18 groups on 7 levels according to the recommended frequency of consumption. The foods that should be consumed most often are located at the bottom (fruit, vegetables and whole grains), while products that should be eaten rarely (beef meat and sweets) are at the top. The Environmental Pyramid represents the environmental impact of food production and consumption. The DP is based on the Mediterranean Diet (MD), which has been indicated by the FAO as an exemplary sustainable diet (FAO, 2010). The concept of DP was developed by the Barilla Center for Food and Nutrition (BCFN) and it provides a useful framework for guiding food choices that promote both health and sustainability. This can involve choosing foods that have a low environmental impact and are high in nutritional value, such as plant-based foods and sustainably sourced animal products.

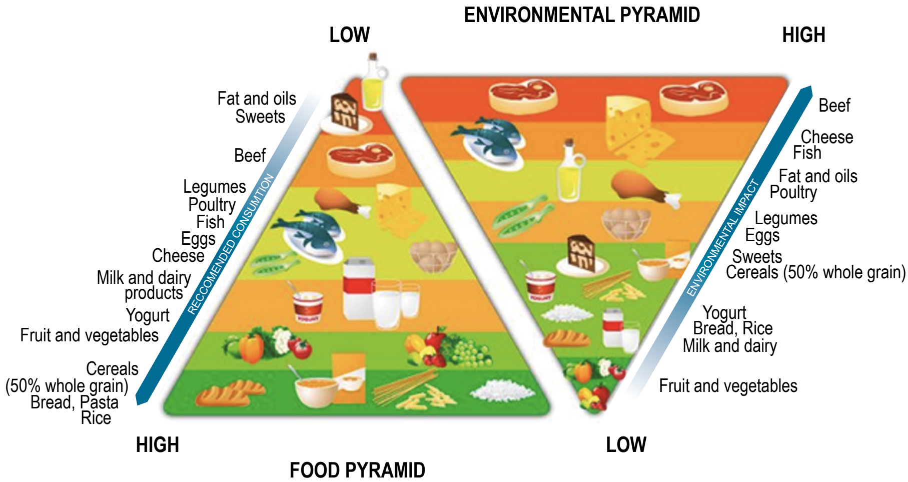

Figure 7.1. Double pyramid for adults
Source: (BCFN, 2014; Ruini, Ciati, Marchelli et al., 2016).

In some countries, governments, health councils and nutritional institutes have started to add sustainability concerns to the traditional FBDG. It should be noted that specific recommendations in individual countries may vary depending on cultural, regional and individual contexts. Sweden, for example, promotes plant-based alternatives, reduces food waste and encourages sustainable agricultural practices. German dietary guidelines suggest limiting meat consumption, choosing plant-based protein sources and considering the ecological footprint of food choices. Finnish Nutrition Recommendations emphasise a plant-based diet and focus on local and seasonal food choices. They promote sustainable fish. The Dutch and Danish governments have implemented programs to reduce food waste, promote organic farming and encourage the consumption of locally produced foods. In Greece, Italy and Spain, the MD has been adopted as a sustainable and healthy dietary pattern (FAO, 2016; Harrison et al., 2022; Szenderák et al., 2022). Polish nutritional guidelines do not explicitly include sustainable development criteria. However, consumers are becoming more and more conscious of the environmental impact of their food choices and are increasingly seeking locally sourced, organic and seasonal food products. There is also a rising demand for plant-based alternatives and a reduction in meat consumption (Raport Roślinniejemy, 2019). Table 7.2 presents recommended daily quantities for six major food groups (protein food, dairy, grains, fruit, vegetables and oils/fats) and total GHGE for exemplary FBDG. A recommended daily intake of protein food ranges from 75 g in India to 167 g as proposed by the EAT-Lancet Commission. The recommended amounts of dairy foods range from 194–300 mL in the EAT-Lancet, Thai and Indian diets to 524–710 mL in Germany and the US. This reflects the importance of dairy products, mainly as contributors to the calcium intake, in Western diets. There is also a big difference between the recommended amounts of grains (184–600 g), fruit (100–784 g) and vegetables (200–512 g). The EAT-Lancet diet recommends the highest oil/fat intake, while the Indian diet recommends the lowest. The total GHGE related to a country's recommended diet may range from 0.86 kg CO_2-eq in India to 3.83 kg CO_2-eq in the United States. It means that the footprint of Indian diet is about 5.2 lower than that of the US diet (Kovacs et al., 2021). The discrepancies in the FBDG are mainly due to cultural and regional differences, as mentioned above.

Table 7.2. Daily recommended amounts of food groups[1] and total GHGE of a diet pattern by country (Seconda et al., 2018)

	Protein foods[a] (g)	Dairy[b] (mL)	Grains (g)	Fruit (g)	Vegetables (g)	Oils/fats (g)	GHGE (total) kg CO_2-eq
US[c]	156	710	170	392	350	27	3.83
US vegetarian[c]	97	710	184	392	350	27	1.80
Germany[d]	99	524	362	250	512	35	2.25
India[d]	75	300	330	100	500	25	0.86
Thailand	135	237	600[e]	784	200	N/A	1.83
EAT-Lancet[f]	167	194	186	160	280	42	1.36

1 – daily recommendations for a 2000-kcal diet, a – including legumes and pulses, b – converted to mL when the FBDG specified dairy products in grams, c – includes recommended amounts of discretionary calories (270 kcal in US, 290 kcal in US vegetarian), d – includes recommended amounts of sugar/sweeteners (32 g in Germany, 30 g in India), e – include roots and tubers, f – the planetary health diet proposed by the EAT-Lancet Commission.
Source: own elaboration.

7.2. Contribution of foods and dietary patterns to SHDs

A sustainable diet typically includes a variety of foods from different food groups, each providing specific nutrients necessary for optimal nutrition. It balances the nutritional needs of individuals with the need to minimise the negative environmental impact of food production and consumption. The environmental and economic costs of food production and consumption can be measured in terms of the resources used, such as land, water and energy, as well as emissions and waste generated during production and disposal. Different food groups have different environmental and economic costs, so the sustainability of a diet may vary depending on the type and amount of food consumed as well as culinary preferences (Aldaya et al., 2021). Eliminating animal products from the current diet has potential to reduce land use (an average reduction of 76%), GHGE (an average reduction of 49%), acidification by 45%–54%, eutrophication by 37%–56%, and freshwater use by 19% for food production. Moreover, reducing consumption of more discretionary products (oils, sugar, alcohol and stimulants) by 20% through avoiding production with the highest land use can reduce both land use (by 39% on average), emissions (by 31%–46%) and freshwater use (by 87% on average) (Poore & Nemecek, 2018).

Table 7.3 shows how different food groups contribute to the concept of a sustainable diet considering various environmental aspects. In Table 7.4, the characteristics and the environmental impact of four dietary patterns (omnivorous, flexitarian, vegetarian and vegan) are compared. As mentioned above, the MD has been indicated by the FAO as an exemplary sustainable diet. It can be considered as a flexitarian diet and is therefore not included in Table 7.4. The MD is based on the traditional dietary patterns of the so-called Mediterranean countries, reflecting their cultural and culinary practices. Its main goal is to improve overall health by preventing disease and reducing the risk of cardiovascular disease, type 2 diabetes, high blood pressure and various types of cancer. It focuses on wholesome foods, plant-based ingredients and healthy fats (particularly polyunsaturated fats from olive oil, nuts and seeds). It allows moderate consumption of fish and poultry, with a limited intake of red meat. The MD, being mainly plant-based, generally has a lower negative impact on the environment compared to diets based largely on animal products. It is indicated that a shift from dietary patterns in Europe and the USA (Western diet) towards the MD can reduce land use by 41% and 55%, water use by 18% and 2%,

Table 7.3. Environmental impact of food groups

Environmental aspects	Explanation	References
	Meat and poultry	
Land use	• Livestock production, including poultry, requires large amounts of land for grazing and to grow feed crops; however, production of beef meat requires about 27 times more land than production of poultry meat • Beef production is particularly land-intensive meat production; it requires 10–17 times more land per unit of protein compared to plant-based protein sources like legumes and grains	Belgacem et al., 2021 Cleveland & Gee, 2017 Poore & Nemecek, 2018
Water use	• Animal agriculture is generally more water-intensive than plant production (significant amounts of water for drinking, sanitation and crop irrigation for feed production) • It takes approximately 15 times more water to produce one kilogram of beef compared to one kilogram of wheat • Water use is about 2.5 higher for beef or pork meat production than for poultry meat	Cleveland & Gee, 2017 Belgacem et al., 2021 Mekonnen & Hoekstra, 2010 Poore & Nemecek, 2018
GHGE	• GHGE are much greater for ruminant animals such as cattle, sheep and dairy than for pigs or poultry. For example, GHGE from beef production (per kilogram) are 7.2–10 times greater than those of poultry • Animal farming accounts for 70% of GHGE in EU agriculture	Belgacem et al., 2021 Chai et al., 2019 EC, 2020 Hannah & Roser, 2020 Heller et al., 2020

Table 7.3 – cont.

Environmental aspects	Explanation	References
Other	• Animal agriculture generates vast amounts of waste, including manure, which can pose challenges for proper management • Poorly managed manure can contribute to GHGE and pollutants entering the environment • Animal welfare has not yet been incorporated into the EU sustainability policy	Cleveland & Gee, 2017 EC, 2020
Cereals and legumes		
Land use	• Cultivation requires significant land use • Clearing land for agricultural purposes can lead to deforestation, habitat loss and biodiversity decline • Compared to animal agriculture, the land footprint of plant-based crops is generally lower. For example, producing a gram of protein from legumes may require about 10–17 times less land compared to producing the same amount of protein from beef • Sustainable land management practices, such as agroforestry and organic farming, can minimise the negative environmental impact	Aldaya et al., 2021 Grosso, Fresán et al., 2020 Poore & Nemecek, 2018
Water use	• Production sometimes requires substantial water usage for irrigation (e.g. rice). The global average water footprint for rice is about 2,500 litres per kilogram • Efficient irrigation methods and water conservation strategies can help to reduce the environmental impact	Mekonnen & Hoekstra, 2010
GHGE	• Production and transportation involve energy-intensive processes, including machinery operation and processing • Compared to animal agriculture, plant-based crops generally have a lower carbon footprint • Implementing energy-efficient technologies and optimising supply chain logistics can reduce negative environmental impacts	Aldaya et al., 2021 Chai et al., 2019
Pesticide and fertiliser use	• Excessive use of pesticides and nitrogen/phosphorus-containing fertilisers can contribute to water and soil pollution, soil acidification, water eutrophication, and it can have a negative impact on biodiversity and human health • Sustainable agricultural management practices, such as organic farming, can reduce pesticide use and minimise the negative environmental impact	Awuchi et al., 2020
Dairy and dairy alternatives		
Land use	• Production requires significant land for grazing cows and growing animal feed crops. This can lead to deforestation • Plant-based dairy alternatives have the potential to reduce land use requirements if they are based on crops with lower land requirements. For example, land requirements for lupine-based cheese production are 0.02 ha per 100 kg/year, while 0.1 ha is needed to produce the same amount of cow milk-based cheese	Kanyama et al., 2021 Reijnders & Soret, 2003

Table 7.3 – cont.

Environmental aspects	Explanation	References
Water use	• Production requires large amounts of water for animal drinking and crop irrigation for feed production • Compared to plant-based milk, cow's milk production uses 2–20 times more freshwater • The water footprint of plant-based dairy alternatives can vary depending on the specific crop and farming practices used	Kanyama et al., 2021 Poore & Nemecek, 2018
GHGE	• Production, particularly from cows, is associated with significant GHGE, primarily in the form of methane • Plant-based alternatives generally have lower GHGE compared to dairy milk. For example, 9–12 times lower emission was noted for the production of lupine-based cheese than for cheese production based on cow's milk	Cleveland & Gee, 2017 Peterson & Mitloehner, 2021 Reijnders & Soret, 2003
Waste	• Dairy farms generate significant amounts of manure, which can contribute to water and soil pollution • Sustainable waste management practices are crucial for minimising environmental impacts	Peterson & Mitloehner, 2021 Poore & Nemecek, 2018
	Fruit and vegetables	
Land use	• Cultivation requires relatively less land compared to animal agriculture	Poore & Nemecek 2018 Reijnders & Soret, 2003
Water use	• Production can have varying water requirements depending on the specific crop • Sustainable water management techniques, such as drip irrigation and precision farming, can help reduce water usage	Mekonnen & Hoekstra, 2010 Poore & Nemecek, 2018
GHGE	• Crop production is responsible for about 20% of the whole food emissions and generally has a lower carbon footprint compared to animal-based foods • Promoting local and seasonal products as well as optimising supply chains can reduce negative environmental impacts	Hannah & Roser, 2020 Poore & Nemecek, 2018
Pesticide and fertiliser use	• Excessive use of pesticides and nitrogen/phosphorus-containing fertilisers can contribute to water and soil pollution, soil acidification, water eutrophication, and it can have a negative impact on biodiversity and human health • Organic farming methods or integrated pest management practices can reduce pesticide use and the negative environmental impact	Özkara et al., 2016
Waste	• Fruit and vegetable waste (e.g., peel fractions, pulps, pomace and seeds) account to about 16% of total food waste and contribute to about 6% to global GHGE • Minimising food waste through improved harvesting, storage, distribution and consumer practices is crucial for reducing the environmental impact	Cassani & Gomez-Zavaglia, 2022 Cleveland & Gee, 2017
	Fats and oils	
Land use	• Production can involve significant land use, especially for crops like oil palm trees. The expansion of oil palm plantations has been linked to deforestation in tropical regions, causing habitat loss, declining biodiversity and contributing to climate change	Awuchi et al., 2020 Poore & Nemecek, 2018

Table 7.3 – cont.

Environmental aspects	Explanation	References
Water use	• Production can require substantial water resources, both for irrigation and processing	Poore & Nemecek, 2018
GHGE	• Deforestation associated with palm oil production releases significant amounts of carbon dioxide, increasing GHGE. • Burning of land for oil palm plantations contributes to air pollution	Poore & Nemecek, 2018

Source: own elaboration.

Table 7.4. Characteristics and environmental impact of selected dietary patterns

Diet	Characteristics	Advantages	Disadvantages	Environmental impact*	References
Omnivorous	An omnivorous diet does not exclude any foods or food groups. It is a typical Western diet including meat and other animal-based foods. In Europe, omnivores make up about 70% of the population	The omnivorous diet, which includes a variety of plant and animal foods, provides all the necessary nutrients. If well balanced, there is no need to use fortified foods or supplements	Animal agriculture can have negative environmental impacts (see Table 7.3)	7 omnivore portions per day: • carbon footprint—6,556 • water footprint—4,639 • ecological footprint—38.1 A 2140-kcal menu: • carbon footprint—7,058 • water footprint—5,031 • ecological footprint—42.0	Ruini, Ciati, Pratesi et al., 2015 Kovacs et al., 2021 Ruini, Ciati Marchelli et al., 2016
Flexitarian	A flexitarian diet can be broadly defined as a semi-vegetarian, plant-based diet that includes dairy, eggs and fish, and allows occasional meat consumption. It offers flexibility and personalisation in food choice and is not tied to any specific cultural or geographical region. It is estimated that between 10% and 30% of Europeans are now flexitarians	It promotes a variety of plant-based foods, including fruit, vegetables, whole grains, legumes, nuts and seeds. It contributes to the preservation of agricultural biodiversity. This diversity supports sustainable agricultural practices, helps maintain resilient ecosystems and protects endangered plant species	The flexitarian diet, although occasionally, still allows the consumption of animal products (animal farming inherently has a negative impact on the environment)	5 vegetarian and 2 omnivore portions per day: • carbon footprint—3,613 • water footprint—2,421 • ecological footprint—21.5	Ruini, Ciati, Pratesi et al., 2015

Table 7.4 – cont.

Diet	Characteristics	Advantages	Disadvantages	Environmental impact*	References
Vegetarian	It excludes meat, including seafood and poultry. However, it typically allows for the consumption of other animal-derived products such as eggs, dairy and honey, depending on the specific type of the vegetarian diet (e.g. lacto-vegetarian, ovo-vegetarian, lacto-ovo-vegetarian)	A well-balanced vegetarian diet tends to be reach in fibre, vitamins, minerals and antioxidants, while being lower in saturated fat and cholesterol. It can support a correct body weight, reduce the risk of chronic diseases and promote overall well-being. For many people, the vegetarian diet is consistent with their beliefs and ethical values. Giving up the consumption of animal products reduces animal suffering and promotes animal welfare. This ethical dimension of vegetarianism contributes to more sustainable food	Although the vegetarian diet may be nutritionally adequate, it requires careful attention to ensure sufficient intake of certain nutrients, particularly vitamin B12, calcium, iron and zinc. Adopting the vegetarian diet can be socially and culturally challenging, especially in communities where meat consumption is deeply rooted in traditions	7 vegetarian portions per day: • carbon footprint—2,436 • water footprint—1,533 • ecological footprint—14.8 A 2393-kcal menu: • carbon footprint—2,598 • water footprint—2,305 • ecological footprint—16.1	Ruini Ciati, Pratesi et al., 2015 Kovacs et al., 2021 Ruini, Ciati, Marchelli et al., 2016 Rosi et al., 2018
Vegan	It excludes all animal products and any other ingredients or products derived from animals, such as gelatine, honey, eggs, dairy products, animal-based additives (colourings: cochineal or carmine, some food flavourings, as well as emulsifiers or stabilisers)	The vegan diet, like the vegetarian diet, generally has a lower environmental impact compared to diets containing significant amounts of animal products	Vegans, excluding all animal-based foods, should take care of wholesome proteins. They should also rely on fortified foods (e.g. plant-based milk, breakfast cereals) or take supplements to meet their vitamin B12 and calcium needs	7 vegan portions per day: • carbon footprint—1,683 • water footprint—1,389 • ecological footprint—13.8 A 2326-kcal menu: • carbon footprint—2,336 • water footprint—2,455 • ecological footprint—14.5	Ruini, Ciati, Pratesi et al., 2015 Kovacs et al., 2021 Rosi et al., 2018

* Carbon footprint in g CO_2eq; water footprint in litres/capita/day, ecological footprint in global m^2.

Source: own elaboration.

GHGE by 36% and 44%, eutrophication potential by 36% and 31% in Europe and the USA, respectively. In term of land use and GHGE, the Western diet is more impactful because it is characterised by high consumption of beef (Belgacem et al., 2021). Moreover, the MD promotes the use of locally sourced and seasonal foods. This helps to reduce GHGE associated with food transport and supports local agriculture systems and producers. This corresponds well to the economic and sociocultural aspects of HSD (Table 7.1). However, some components of the MD, such as certain fruit, vegetables and olive oil, may be less available or more expensive in some countries. This can be a problem for people with limited financial resources to follow the diet. Strict adherence to the traditional MD, which is deeply rooted in the cultural traditions of the Mediterranean countries, may not be compatible with the cultural or dietary preferences of people with different backgrounds.

The data published show that plant-based diets, although plant crops require significant use of land and water, have a lower negative environmental impact compared to animal agriculture and diets including meat (Table 7.3 and 7.4). The results of the NutriNet-Santé cohort study (Seconda et al., 2018) conducted in France showed that diets with high GHGE (ranging from 2318 to 4099 kg CO_2-eq/year) contained more animal-based food and provided more calories, and diets with low GHGE had a high nutritional quality. Moreover, primary energy consumption (ranging from 3978 to 8980 MJ/year), land occupation (ranging from 1693 to 7188 m^2/year), and monetary diet cost (from 6.89€ to 7.68€/year) increased with GHGE. The authors of the study also observed that participants with lower GHGE diets were the highest organic food consumers.

Conclusions

Many countries include sustainability in their dietary guidelines, but only a few have already incorporated the quantitative recommendations based on nutrition and sustainability considerations. To strike a balance between nutrition and sustainability, it is recommended to reduce the consumption of meat and meat products in favour of fruit and vegetables, encourage the consumption of plant-based protein substitutes and avoid food waste. Dietary patterns which include a variety of plant products with occasional consumption of meat provide all the necessary nutrients and have a lower negative impact on the environment. Promoting local and seasonal products and optimising supply chains can also reduce negative environmental impacts of such diets and contribute to territorial economic growth. Respecting cultural habits and food preferences is essential for food acceptance. When they are culturally acceptable and affordable, they can be regarded as SHDs. Every consumer, through conscious food choices, can follow a healthy sustainable diet, regardless of whether the national FBDG incorporate the sustainability aspects.

Abbreviations

FBDG – food-based dietary guidelines
GHGE – greenhouse gas emissions
MD – Mediterranean diet
SHDs – sustainable healthy diets

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8. MEAT ALTERNATIVES—MARKET AND CONSUMPTION

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Abstract

Elimination of animal-based products, often related to a vegetarian or vegan diet, is one of the most popular nutritional trends observed around the world. This chapter provides an overview of the assortment, market and consumption of various meat alternatives. Products replacing meat are made of various types of (mostly) plant-based raw materials including pulses/legumes, cereal proteins (mainly gluten), oilseeds, fungi (edible mushrooms) and algae; however, cultured meat and edible insects are also described. The market of meat alternatives was estimated at USD 10,11 billion in 2022 and is expected to grow at a compound annual growth rate (CAGR) of minimum 15% by 2030. Europe has the largest share (52%) of the global market followed by North America (27%), Asia Pacific (12%), Latin America (6%) and Middle East and Africa (4%). The top producers are Beyond Meat, Boulder Brands, Hain Celestia, Nestlé, Garden Protein International, Vivera, Lightlife Foods, Woolworths, Naturli' Foods and Sainsbury's. Despite the fact that vegetarians and vegans constitute 6.4% and 6% of global consumers, respectively, more and more people are willing to either reduce the consumption of meat (62%) or animal-origin (42%) products. This is due to the fact that the consumption of meat-free products plays a role in sustainable development considering multiple health, economic and environmental issues.

Keywords: diet quality, environmental impact, meat alternative, meat-free, sociocultural acceptability, sustainable nutrition, vegan, vegetarian.

JEL codes: D12, D13, I11, I12, I15.

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Introduction

Elimination of animal-based products, generally called a vegetarian or vegan diet, is one of the most popular nutritional trends observed around the world, which results also from the obligation to follow a vegetarian diet in individual religious sections (Ahmad et al., 2022). Consumption of meat-free products also plays a role in sustainable development considering multiple health, economic and environmental issues. Therefore, this chapter provides an overview of the global market of meat-free products. It also describes the popularity and consumption of selected meat, dairy and egg alternatives.

Meat is an important source of protein, which delivers all essential amino acids necessary for human health. It is also highly valued by many consumers due to favourable sensory properties such as texture and flavour (Zahari et al., 2022). However, meat consumption has raised various ethical, health and environmental concerns. Therefore, over the past years, consumers have shifted their eating patterns, seeking dietary alternatives (Starowicz et al., 2022). Meat alternatives refer to meat-free products that try to mimic traditional meat. Meat alternatives are (mostly) plant-based, high-protein products that can replace food of animal origin (Czerwinska, 2020). However, cultured meat and edible insects should also be considered as meat alternatives. All these types of products are called meat alternatives, as well as meat analogues, meat substitutes, mimic meat, mock meat, vegetarian meat, plant-based meat, synthetic meat, amalgam meat or health-promoting meat (Ahmad et al., 2022; Vallikkadan et al., 2023), and are described in paragraph "Assortment of meat alternatives".

Based on plant raw materials, high-protein products are foods with a positive, targeted effect on the human body. The growing awareness of consumers regarding the way of eating in order to maintain health and good condition increases interest in protein sources alternative to animal products (Hoffmann & Jędrzejczyk, 2010). There are many health benefits associated with eating meat analogues. Reduced consumption of animal meat can help primarily in lowering cholesterol levels as well as reduce the risk of developing cardiovascular diseases such as heart attack or stroke. In contrast, daily consumption of animal meat increases the risk of developing colorectal cancer (Hu et al., 2019). A particularly high health risk is associated with the consumption of red meat and processed meat in the amount exceeding 500 g per week (Herforth et al., 2019).

Meat alternatives, in addition to supporting people's health and well-being, also help to mitigate the negative impact of production and consumption of animal meat on the environment. Undeniably, meat production burdens the environment. It consumes a large amount of the earth's resources and drinking water. It causes environmental pollution, greenhouse gas emissions, loss of terrestrial and aquatic biodiversity, and increases the risk of animal diseases (Van der Weele et al., 2019).

According to Ahmad et al. (2022), currently about 30% of global warming and climate change has its source in the food industry. Global animal production requires about 2,400 Gm^3 of water per year, and as much as 70% of global freshwater is used for agriculture. For example, the average water footprint per calorie of beef is twenty times higher than that of cereals and root crops (Mekonnen & Hoekstra, 2010). In addition, meat production contributes to eutrophication, i.e. pollution of water and ecosystems with excessive content of nutrients, which is a serious environmental problem. According to a report presented in 2018, producing one kilogram of beef contributes to the emission of 365 g of phosphate equivalent (PO_4eq) (Poore & Nemecek, 2018). Despite the fact that phosphates are not harmful to humans, their presence in water disturbs the balance of aquatic organisms, causing algal blooms, which can already have a direct (negative) impact on the health of people living in nearby areas (Kleinman et al., 2011). Moreover, another research shows that people who follow meat-free diets have a real influence on reducing the negative impact on the environment. A study from 2017 comparing the impact of different diets, both meat and meat-free on the environment, took into account three indices considered to be the most representative for the agri-food system, i.e. carbon footprint—expressed as gCO_2 eq/kg, including greenhouse gas emissions, water footprint—expressed in L/kg of water resources consumption and ecological footprint—expressed as global m^2/day of biologically productive land/sea needed to produce a food product unit (Rosi et al., 2017). An analysis of the environmental impact of these three types of diet showed that the animal-based diet had a significantly greater impact on each of the environmental indicators compared to the others. For example, the average CO_2 emission for a traditional (meat) diet, expressed as an average of 7 days, was about 3960 gCO_2 eq/kg, while the average for a vegan diet was about 2340 gCO_2 eq/kg. Similar disproportions were also shown for the ecological footprint. On average, about 26 m^2 of land/water resources per day were used for the production of traditional (meat) diet ingredients, while in the case of vegan products, it was about 14.5 m^2.

Therefore, consumers' awareness of health, environmental sustainability and animal welfare has shifted people's attention from the meat of animal origin to the meat of plant origin and the scale of this trend (market and consumption) is described in the following sections.

8.1. Assortment of meat alternatives

The market of meat substitutes is mostly associated with vegetable-based products. However, cultured meat and edible insects should also be considered as potential meat alternatives. Plant-based meat analogues can replace traditional meat, being a nutritionally sustainable source of protein (Choudhury et al., 2020). Meat substitutes as alternative sources of animal protein, based on plant raw materials, are produced using various plant proteins, such as oilseed proteins, cereal proteins, legume proteins and leaf proteins. Oilseed proteins are obtained from soybean, canola, sunflower weed, sesame, chia seeds, pumpkin, grape seeds, linseed, and cereal proteins are obtained from wheat, corn, rice, barley, sorghum and amaranth (Czerwinska, 2020; Kurek et al., 2022; S. Y. Lee et al., 2023).

Animal protein substitutes can be traditional protein foods of plant origin, which are used as a substitute for meat protein, for example, tofu or seitan (Vallikkadan et al., 2023). Substitutes can also be foods that are not only a source of protein but are also consciously designed so that their taste and structural properties imitate meat through the use of plant ingredients, called plant-based meat analogues (PBMA) (Huang et al., 2022; S. Y. Lee et al., 2023). Vallikkadan et al. (2023) referred to these substitutes as meat fillers and meat analogues. Meat fillers are products that are used to replace fresh meat of animal origin. Meat analogues, on the other hand, are foodstuffs that mimic meat of animal origin. Such products are similar in appearance and structure to muscle meat (Vallikkadan et al., 2023). Their texture, colour, flavour and aroma may reflect specific types of meat (Ahmad et al., 2022). Such meat substitutes may also offer a similar nutritional composition as traditional meat, but with many additional ingredients and a high level of processing (Bohrer, 2019).

Table 8.1 shows products that can replace meat of animal origin, made of various types of raw materials: pulses/legumes, cereal proteins (mainly gluten), oilseeds, fungi (edible mushrooms), algae, cultured meat or edible insects.

Table 8.1. Most popular plant-based meat alternatives

Meat alternatives sourced from pulses/legumes	
Tofu	Made from soybeans, also referred to as soya curd. Made by curdling fresh hot soy milk with a coagulant. It comes in the form of blocks and contains high amounts of protein, calcium and iron (Obatolu, 2008). Tofu is widely used around the world as an alternative to meat in the food industry (Singh et al., 2021)
Tempeh	It is made by fermenting soybeans. It is a product with a hard texture and consistency similar to a rubber mushroom (chewy mushroom). It is rich in protein and fibre and contains vitamin B-12, which is a by-product of the fermentation process (Babu et al., 2009)
Yuba	Yuba is a protein-fat skin that forms on soy milk and has a characteristic slightly rubbery texture. It is mainly used to produce meat analogues or as an addition to soups and desserts. When fried, it forms a layer imitating roasted chicken skin (Hoffmann et al., 2009; Singh et al., 2021)
Kinema	A soybean fermented alkaline meat substitute (Sarkar et al., 1994)
Soy concentrates	Soy protein concentrate contains about 70% protein. Used as an additive to meat substitutes. Mainly used for making such products as: sausage, luncheon meat, pâté or burger (Hoffmann et al., 2009)
Soy isolates	The most concentrated source of protein, min. 90%. In vegetarian products, they are used as an enriching substance for the production of meat analogues (Hoffmann et al., 2009)

Table 8.1 – cont.

Soy protein textures	TVP (Textured Vegetable Protein) is obtained in the extrusion process from flour, concentrate or soybean isolate. It contains from 50% (flour textures) to 65%–70% protein (concentrate textures), with a fat content of less than 1% and no more than 3.5% fibre (Hoffmann et al., 2009)
Meat alternatives sourced from cereals	
Seitan	Called wheat meat in vegetarian cuisine because the main ingredient is wheat flour. Seitan has a texture very similar to meat. It is a source of protein, iron, B vitamins and small amounts of fat (Hoffmann & Jędrzejczyk, 2010; Singh et al., 2021)
Wheatpro	A product derived from wheat gluten, transformed and extruded to give it a meat texture. It is available on the market in the form of flakes, ground or chopped (Singh et al., 2021)
Arrum	It is a converted mixture of gluten and pea proteins in a 1:1 ratio. The finished product resembles pieces of meat in appearance and structure. It is used to produce, for example, lasagne or dumplings (Hoffmann & Jędrzejczyk, 2010)
Trivall	It is obtained from wheat gluten and vegetables protein. Available in frozen form, ready to eat after heating, in the form of analogues of burgers, sausages, nuggets or schnitzels (Hoffmann & Jędrzejczyk, 2010)
Meatless	Vegetable fibres obtained from sweet lupine seeds, seaweed and wheat. Meatless is a semi-finished product with a texture typical of meat (Hoffmann & Jędrzejczyk, 2010; Singh et al., 2021)
Meat alternatives sourced from fungi (edible mushrooms)	
Quorn	Meat substitute, the main ingredient of which are mycoproteins derived from the mold strain *Fusarium venenatum*, which occurs naturally in the soil. The obtained mycoproteins are purified, dried and mixed with egg white (in the vegan version, potato protein is used as a binder). The product is sold in many countries around the world both as a semi-finished product for further processing and in the form of ready meals (chops, sausages) (Jurek, 2019)
Meat alternatives sourced from oilseeds	
Fibres	Product obtained from sweet lupine seeds after mixing with wheat flour (Singh et al., 2021)
Meat alternatives sourced from microalgae	
Remis algen	An algae-based product. Algae mixed with other potential plant proteins such as cereals, rice or cooking oils (Singh et al., 2021)
Meat alternatives sourced from cultured meat	
In-vitro meat	Also called lab-grown meat; it is artificial meat produced using stem cell technology. Comes from farm animals, so it is very similar to regular meat (H. J. Lee et al., 2020; Van der Weele et al., 2019)
Genetically Modified Organisms (GMO)	Meat of genetically modified animals (H. J. Lee et al., 2020)
Meat alternatives sourced from edible insects	
Extracted protein from insects	Insects used as food resources. A valuable source of protein due to their high protein content with essential amino acids sufficient to meet our daily needs (H. J. Lee et al., 2020)
Whole insects	Low acceptance of insect eating among Western consumers. In Africa, South America and Southeast Asia eating insects is an ancient custom (H. J. Lee et al., 2020; Van der Weele et al., 2019)

Source: own elaboration.

8.2. Market of meat alternatives

There are many manufacturers of meat substitutes operating at the national (Polish) and international market. Research conducted in 2022 among Poles indicated the Tarczyński brand as a top brand of plant-based meat alternatives. Almost half of the respondents (45%) declared that they add meatless products of this manufacturer to their shopping list. The respondents also chose the GoVege (21%) and Vemondo (14%) brands (Table 8.2) (Statista, 2022). The world's most popular plant-based meat analogue brands are also listed in Table 8.2.

Table 8.2. Most popular plant-based meat alternatives brands in Poland and around the world

POLAND		WORLD
Brand	**Share of users (%)**	**Brand (alphabetical order)**
Tarczyński	44.7	Beyond Meat
GoVege	21.1	Boulder Brands
Vemondo	13.7	Hain Celestia
Dobra Kaloria	6	Nestle
Garden Gourmet	5.2	Garden Protein International
Olewnik	2.2	Vivera
Ona Day More	2	Lightlife Foods
Z Gruntu Dobre	1.5	Woolworths
Well Well	0.8	Naturli' Foods
BezMięsny	0.7	Sainsbury's
Other	2.2	

Source: based on (Boukid, 2021; Statista, 2022).

The market of meat alternatives continues to grow due to the increasing demand for plant-based products visible around the world (Singh et al., 2021). Throughout the world, it has recorded systematic increases in recent years. The value of vegetable meat sales around the world in 2022 was estimated at USD 10,11 billion (Statista, 2023b). Forecasts indicate that this number will continue to grow over the next few years and will reach approximately USD 33,99 billion in 2027 (Figure 8.1) (Statista, 2023b).

The size of the global market for meat alternatives is expected to grow at a compound annual growth rate (CAGR) of 42.1% between 2022 and 2030 (Grand View Research, 2022). Some sources forecast that the global meat substitute market will reach USD 30.92 billion by 2026, with a compound annual growth rate (CAGR) of 14.8% (Singh et al., 2021). The Union Bank of Switzerland (UBS) predicts that the global plant-based meat market will reach $51 billion by 2025 (UBS, 2021). Europe has the largest share in the global market of meat analogue products (51.5%), followed by North America (26.8%), Asia-Pacific (11.8%), Latin America (6.3%)

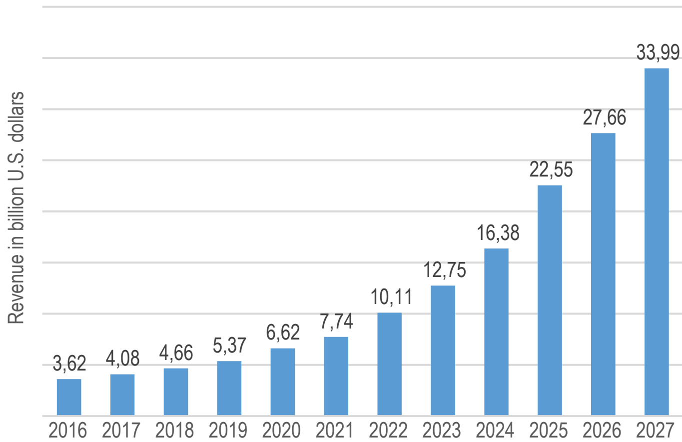

Figure 8.1. Market revenue of plant-based meat worldwide from 2016 to 2027
Source: (Statista, 2023b).

and the Middle East and Africa (3.6%) (Boukid, 2021). Data from 2021 indicate that the country with the largest revenues from the meat substitute market will be China, generating approximately USD 2,1 billion. The US comes in second with USD 1,5 billion, followed by the UK with USD 847 million in revenue. Russia and Germany will also generate high revenues (Statista, 2021d).

In 2020, the North American continent had the largest share of the global plant-based meat market (44%). Western Europe also had a large market share of plant-based alternatives (34%). The Middle East and Africa had a market share of around four percent, Latin America around 3%, and Eastern Europe and Australasia around 2% (Statista, 2021c). In Europe, the leading market for meat alternatives was the UK, with sales more than EUR 502 million. The size of the German market was approximately EUR 357 million and the Dutch market was approximately EUR 174 million. By comparison, sales of meat substitutes in Romania only reached around EUR 5 million in 2020 (Statista, 2020).

In 2015, over 6,485 new plant-based meat analogues appeared on the global market (Huang et al., 2022). A report published by the Good Food Institute indicates that in 2019, the best-selling categories of plant-based meat substitutes were burgers, with sales of USD 283 million, links (sausages and hot dogs) (USD 159 million) and patties (USD 120 million) (GFI, 2021). The market for meat and meat substitutes is expected to change in the coming years 2025–2040. Today, the market is dominated by traditional meat products. This dominance is expected to continue until 2025. However, in the coming years, this trend will decrease, and in 2040, these products will constitute a minority of available products. In 2040, the market is expected to consist of about 40% of traditional meat products, about

35% of farmed meat or lab-grown meat products, and about 25% of vegan meat alternatives (Figure 8.2) (Statista, 2021a).

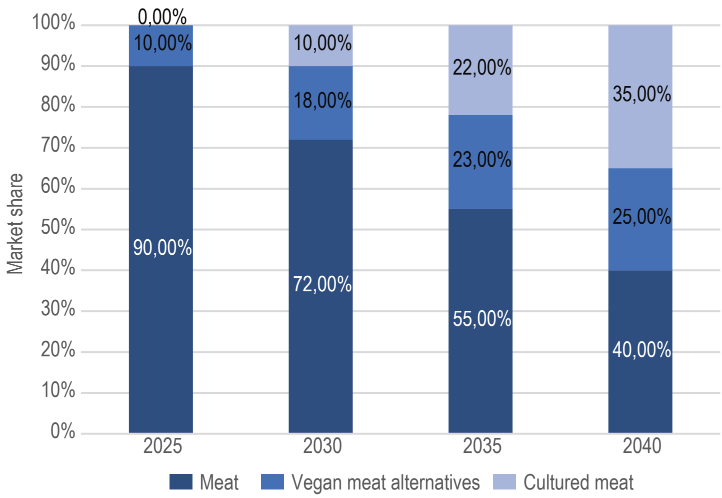

Figure 8.2. Composition of the meat and meat alternatives market worldwide from 2025 to 2040
Source: based on (Statista, 2021a).

8.3. Consumption of meat alternatives

People are increasingly switching to a plant-based diet out of concern for the treatment of animals, the environment or for their own health. Popular plant-based diets include a vegetarian diet—a diet excluding meat and fish, the pescatarian diet—which is largely vegetarian but also includes seafood, and a vegan diet—a type of vegetarian diet that excludes meat, fish and all products of animal origin, such as milk or eggs (Shmerling, 2019).

A meat-free diet is a diet that focuses on plant-based proteins, such as beans, lentils, nuts and soybeans, and may also include dairy and eggs (Lachtrupp, 2021). The term plant-based diet is defined by Hargreaves et al. (2023) as “an eating pattern in which foods of animal origin are completely or mostly excluded”. Plant-based diets have a number of advantages. They contain large amounts of nutrients, vitamins, micronutrients and macronutrients (Singh et al., 2021). Many years of research have shown that plant-based diets are associated with a lower risk of cardiovascular disease, heart disease, obesity, type 2 diabetes and some cancers (compared to diets rich in meat and other animal products) (Kalchenko, 2016). A balanced and varied meat-free diet is suitable for people in all phases of life (Kalchenko, 2016).

Currently, animal meat alternatives are not only consumed by vegans and vegetarians. They are also becoming popular with the wider carnivorous population. According to a recent Nielsen market report, 62% of respondents are willing to reduce meat consumption and 43% would like to replace meat proteins with plant-based products (Huang et al., 2022). A study conducted in 2020 indicated that vegetarians and vegans constitute a small group of global consumers, with vegans amounting to 4% and vegetarians to 6.4%. A larger group of global consumers are people who do not follow a strict meat-free diet but try to limit products of animal origin—they constitute 42% of consumers worldwide (Passport, 2020). In 2021, a survey was conducted in various European countries where respondents answered the question "Do you avoid eating meat?" (Figure 8.3). The study shows that the largest percentage of non-meat eaters in Europe live in Ireland and the British Isles, around 15% of the population. For comparison, consumers living in the Czech Republic and Hungary have the lowest share; they limit meat in negligible amounts, only 5% of the population (Statista, 2021b). In Poland, in 2023, only 8% of respondents declared that they only eat meat alternatives, while 34% admitted that they eat both meat and its alternatives (Statista, 2023a).

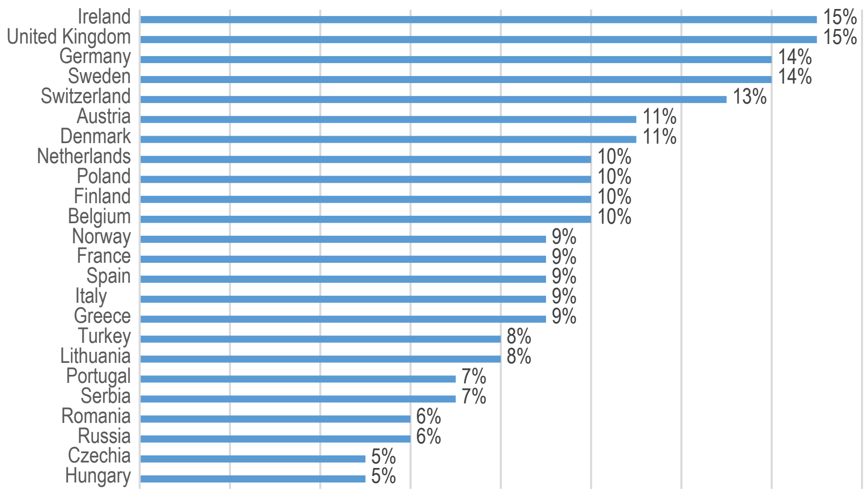

Figure 8.3. Share of vegetarians, vegans and pescatarians in selected European countries in 2021

Source: (Statista, 2021b).

Figure 8.4 shows the share of vegetarians and vegans in selected countries worldwide in 2021 and 2022, respectively. India is the leading country when it comes to the share of vegetarians amongst its population. Almost a quarter of the respondents from India were following a vegetarian diet according to a survey carried out in 2021. Vegetarianism in the United States, by comparison, amounted only to a share of five percent of the respondents. In 2022, around three percent of responding German consumers between 18 and 64 years of age followed a vegan diet. In Brazil, China, Mexico and the U.S. between two and six percent of the respondents are vegan. The noteworthy standout is India where over a tenth of respondents said they typically follow a vegan diet. The survey was carried out among online users.

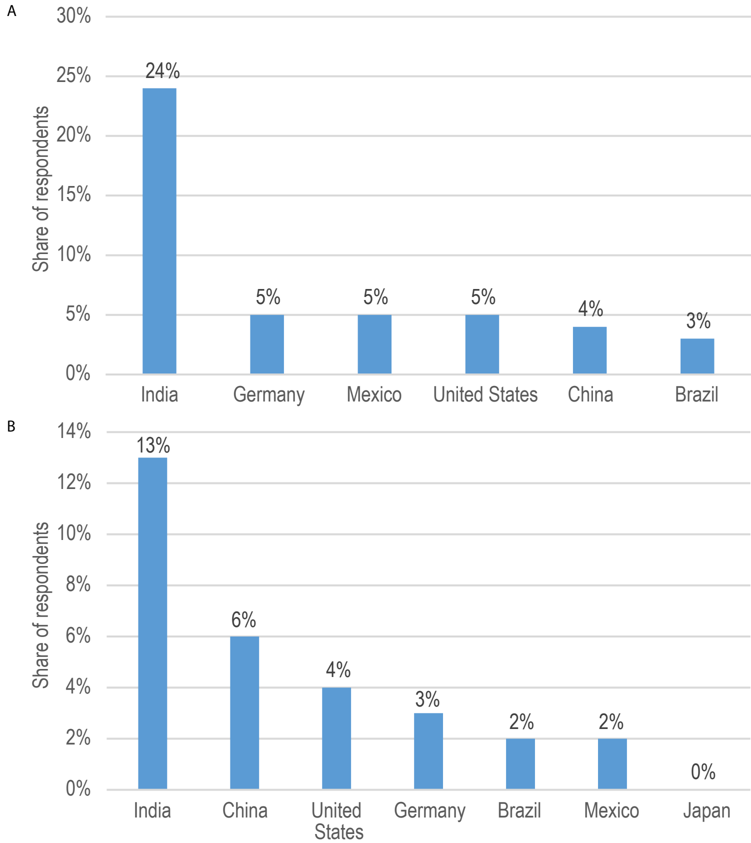

Figure 8.4. Share of vegetarians (A) and vegans (B) in selected countries around the world in 2021 (A) and 2022 (B)
Source: (Statista, 2023c, 2023d).

Conclusions

The chapter provides an overview of the global market of meat-free products and the popularity of meat, dairy and egg alternatives. It discusses the reasons behind the shift towards vegetarian and vegan diets, including ethical, health and environmental concerns. The market for meat alternatives is predominantly plant-based, but it also includes cultured meat and edible insects. Various types of plant-based proteins are used in meat substitutes, such as oilseed proteins, cereal proteins, legume proteins and leaf proteins. The chapter highlights popular brands of meat alternatives and the growth of the market, with estimated revenues reaching USD 40 billion in 2027. Consumer consumption patterns are shifting towards plant-based diets, with an increasing number of people reducing their meat intake or opting for plant-based protein sources. The trend is not limited to vegans and vegetarians, as even carnivorous consumers are embracing meat alternatives these days.

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9. FOOD LABELLING SYSTEM—CONSUMERS' PERSPECTIVE

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Abstract

The information placed on labels is intended to serve consumers by providing them with information about composition, nutritional quality and shelf life of food products as well as to promote waste-prevention behaviour and support sustainable food systems. Even though consumers declare interest in the information on labels, their knowledge of the composition and nutritional value of the products and understanding of this information (e.g., nutritional facts table, minimum durability date: "best before", and "use by" date) is often insufficient. European and international health institutions and societies are now placing great emphasis on developing clear and comprehensive information to consumers about the properties of food products and their impact on health, using legislative instruments and recommendations. The aim of this chapter is to discuss the latest research showing how food labelling can support consumers in their healthy and sustainable purchasing decisions.

Keywords: consumer awareness, sustainable food choices, nutrition labelling, front-of-pack label, date labelling, food waste prevention.

JEL codes: D83, E2, F69, I12, I15, Q01, Q02.

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Introduction

A diagnosis of the current food system has revealed that the present models of food production and consumption do not support sustainable growth in terms of environmental and health concerns (Agyemang et al., 2022). From the environmental point of view, excessive use of natural resources, loss of biodiversity and climate change pose a threat to sustainability. The problem grows as the amount of wasted food increases. Production of food that is not consumed causes not only inefficient use of land, water, fertilisers, labour, energy, fuels and packaging but also generates unnecessary emission of greenhouse gases which contribute to global warming (Bunge et al., 2021). Evidence shows that the present model of food consumption affects human health. Over the last decades, unfavourable trends in food purchasing choices have been observed. The globalisation and industrialisation of the agri-food sector have strongly affected the diet composition in Western countries (Clodoveo et al., 2022). The shift towards an unbalanced diet has contributed to a growing number of people becoming overweight or obese. Increasing body mass indices (BMI) are associated with rising global incidences of chronic non-communicable diseases, especially type II diabetes, coronary heart disease and some cancers (Perdomo et al., 2023). It was estimated that in 2017 in the EU over 950,000 deaths (one out of five) and over 16 million lost healthy life years were attributable to unhealthy diets (European Commission, 2020). Considering the above facts, the transition of food consumption patterns towards sustainable and healthy diets is one of the greatest global challenges (FAO & WHO, 2019). Although it was found that diets representing the highest nutritional quality (e.g., pescatarian diet) are not those with the lowest carbon footprints such as plant-based diets, it was suggested that improvements in both diet quality and carbon footprint can be attained simultaneously in some cases (e.g., DASH or Mediterranean diets) (O'Malley et al., 2023).

Informing consumers via food labelling constitutes a valid entry point for policy intervention aiming at promoting sustainable food consumption and facilitating the shift to healthy, sustainable diets (Carlsson et al., 2022; Potter et al., 2023). In the EU, relevant initiatives are going to be introduced, covering harmonisation of labelling on the nutritional, environmental, climate and social aspects of food products. Particular attention is paid to nutrition labelling (including the proposal for mandatory front-of-pack nutrition labelling and information about nutrient profiles) to enable consumers to make informed, conscious health choices and restrict the promotion of foods high in sugars, fats, salt and meat (European Commission, 2020). There is an ongoing discussion on the role of date marking ("best before" and "use by" dates) in shaping the food waste behaviour. Several studies have shown that the misunderstanding and misuse of the "use by" and minimum durability date ("best before") lead to food waste (Gong et al., 2022; Kavanaugh

& Quinlan, 2020; Patra et al., 2022). According to the ongoing discussion, the extension of the list of foods for which the "best before" date would not be required, e.g. coffee, tea, pasta or rice, is considered (European Commission, 2020). The second discussed option is improving the expression and presentation of the date marking. Finally, keeping only one date related to safety issues is considered.

According to the latest studies, date labelling in some cases may promote waste behaviour, but in some others, it may favour waste-prevention behaviour. Hence, the date marking can be used as an intervention tool (Sielicka-Różyńska & Samotyja, 2023). Understanding consumer's perception of food labelling is a prerequisite for future system improvement in order to use the potential of food labelling in promoting sustainable consumer choices and providing consumers' health and safety (Holenweger et al., 2023; van Bussel et al., 2022). The aim of this chapter is to discuss the latest research showing how food labelling can support consumers in their healthy and sustainable purchasing decisions.

9.1. Front-of-pack nutrition labelling

The objectives of nutrition labelling policy are generally threefold: to provide interpretive information to consumers to make healthier food choices, to encourage the food industry to reformulate their products towards healthier options, and finally, to allow governments to influence public health in a non-enforcing, voluntary way (Van Kleef & Dagevos, 2015; Vandevijvere et al., 2020). Nutrition labelling informs consumers about the nutritional properties of food products through two components: a) nutrient declaration (i.e. detailed qualitative and quantitative information about the nutrient content) and b) supplementary nutrition information, which intends to assist consumers to understand the nutritional value of food products (Codex Alimentarius Commission, 2021).

Most countries require mandatory nutrition information to be displayed on food labels in the form of a nutrition facts table or panel located on the back or side of the package; however, consumers usually find it difficult to fully understand numerical information (Franco-Arellano et al., 2020). Simple graphical information has been reported to be more efficient in influencing healthfulness perception and food choice intention (Ares et al., 2018). For this reason, front-of-pack (FOP) nutrition labelling schemes have been developed to convey supplementary information through simple graphical information. FOP nutrition labels are usually well accepted by both consumers and the industry (Ares et al., 2018; Hau & Lange, 2023; Mhurchu et al., 2017). They vary in presentation including the shape, colour, size and type of public health nutrition message as well as nutrient focus (focus on positive and/or negative nutrients) (Kanter et al., 2018). FOP nutrition labelling has been implemented worldwide through government policies in a countless ways using different terminology. In Table 9.1, a list of commonly used terms in the FOP labelling is presented.

Table 9.1. Various types of front-of-package nutrition labelling (FOP-NL) schemes

Type of FOP-NL	Description	Examples
Endorsement logos	combine nutritional criteria with other food-related criteria to give an overall assessment of the healthfulness of a product, with positive judgement	• health logos (e.g., Keyhole symbol) • choice logos
Nutrient-specific warning label	provides information about the surplus quantity of an individual nutrient in relation to a pre-established threshold, with negative judgement	• warning labels
Reductive system	shows information only, with no specific opinion or recommendation	• Guideline Daily Amount (GDA) system / Reference Intake (RI)
Interpretive nutrition rating system (INRS) / Summary system	provides nutrition information as guidance rather than specific facts	• nutri-score • star-based systems (e.g., HSR) • traffic light symbols

Source: (Santos et al., 2020; Vandevijvere et al., 2020).

FOP nutrition labelling is receiving increasing attention worldwide as a strategy to guide consumers towards healthier food choices. Different variants of interpretive schemes have been recently implemented in several countries. They largely differ in the type of information, their graphic representation and the underlying nutrient profiling method used to rank product healthfulness based on the nutritional composition. Main logos described as follows are pictured in the scheme presented in Figure 9.1.

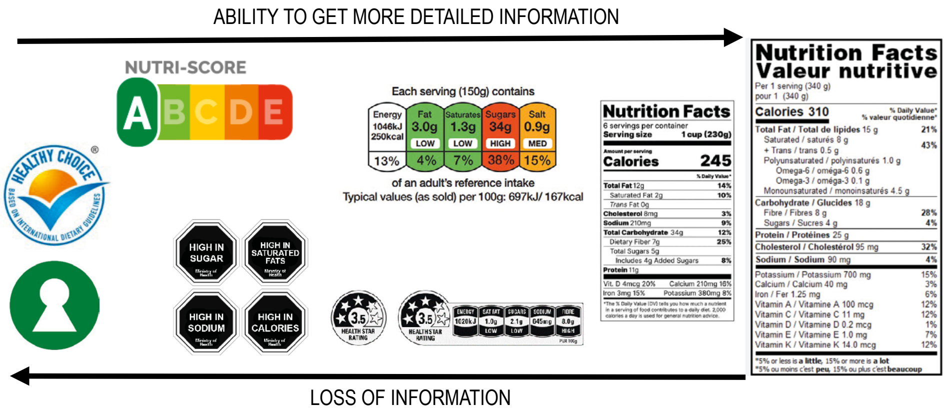

Figure 9.1. Food labelling schemes and their information flow
Source: based on (Roodenburg, 2017).

The first FOP nutrition labelling systems to be implemented were health logo systems. The Keyhole logo was the first logo system introduced in 1989, mainly in the Nordic countries. The Choice logo is another positive front-of-pack logo for food and beverage products. It identifies healthier food products within a product group. Health logos are pictured health claims rather than interpretive FOP nutrition labelling (Kanter et al., 2018).

Another tagging system is the colour warning system, which is a nutrient-based scheme that highlights products which exceed the limits for nutrients associated with non-communicable diseases. The limited nutrients are calories, sugars, saturated fatty acids and sodium (Vandevijvere et al., 2020). It is presented as a graphic and lettering colour pictogram, which determines the overall nutritional value of foodstuffs.

Summary FOP nutrition labelling schemes that provide a global overview of the product nutritional quality, commonly called healthfulness, are such systems as the French Nutri-Score and the Australian Health Star Rating (HSR). The Nutri-Score classifies products into five categories of different nutritional quality, each associated with a different colour and letter: green for the highest nutritional quality (A) and red for the lowest nutritional quality (E). On the other hand, the HSR classifies products into 10 categories of nutritional quality, using the star rating exclusively, which ranges from 0.5 (least healthy) to 5 (most healthy) stars. The number of stars that are displayed is based on the nutrient profile of the food, typically incorporating both positive and negative nutrients (Franco-Arellano et al., 2020; Roodenburg, 2017). One of the best-known variants of interpretive nutrition labelling schemes is the United Kingdom multiple traffic light label scheme, in which total fat, saturated fat, sugar and sodium contents are colour coded as either high (red), medium (amber) or low (green). Colour coding is based on thresholds for nutrient amounts. Nonetheless, different representations of the labelling systems result in more or less detailed nutrition information conveyed to the consumer. In brief, a more graphic representation often results in significantly less detailed information for the consumer (Figure 9.1).

Since 2017, the Nutri-Score has been adopted for voluntary use in several European countries. Recently (since 2020) it has also been recommended in Poland, but it is not obligatory for all producers yet (Panczyk et al., 2023). The Nutri-Score classification is based on nutritional content and relies on the nutrient profiling system (NPS) of the British Food Standards Agency (FSA) to judge healthfulness (Hau & Lange, 2023). In this system, a food item receives positive and negative points based on its contents per 100 grams for solid food items or 100 millilitres for beverages. The value of the item is judged by its composition based on a limited number of nutrients and its energy density. There are several factors that the Nutri-Score ignores such as vitamins, caffeine, meat content, antibiotics, pesticides, artificial sweeteners, alcohol and preservatives. Examples of controversial

Nutri-Score ranks for various food items are described in detail, among others, by Roodenburg (2017). The author indicates that the composition of different foods differs and, for this reason, different foods need different sets of criteria to enhance improvement of healthfulness judgement. Panczyk et al. (2023) conducted a Poland-wide expert opinion study and expressed concerns about the Nutri-Score's ability to account for a product's degree of processing and full nutritional value. The authors concluded that Poland's current labelling system needs expansion, but the Nutri-Score requires significant changes and validation against national guidelines and expert expectations before implementation (Panczyk et al., 2023).

Front-of-pack nutrition labelling is voluntary and cannot be used instead of a nutrition declaration. Although there is general agreement on the need to provide simple and readable nutrition information to enable consumers to make more informed purchase decisions, consensus on which interpretational elements are the most appropriate to encourage consumers is still under investigation (Ares et al., 2018).

9.2. Influence of front-of-pack labelling on consumers' perceptions of product healthfulness and purchase intentions

FOP labelling applied parallel to nutrition labelling is the solution to make the health choice an easy one (Roodenburg, 2017). FOP labels are generally considered as more efficient tools for increasing consumers' awareness of the nutritional quality of food products. It has been shown that labels on the front of the package receive more attention than labels on the back of the package (Becker et al., 2015; Bialkova & van Trijp, 2010). Moreover, pictorial elements on a package are recognised better than words, particularly by low-literate consumers (Sielicka-Różyńska et al., 2021; Van Kleef & Dagevos, 2015). The effectiveness of the FOP nutrition labelling schemes is determined by their ability to encourage more healthy dietary patterns. First, the FOP nutrition labelling schemes need to catch consumers' attention (Grunert & Wills, 2007). Bialkova and Van Trijp (2010) indicated that the display size, colour scheme, familiarity with the label and its location on the front of the packaging are key determinants of consumers' attention to nutrition labels. Farther, FOP labels should facilitate understanding of the nutritional value of food and speed up the evaluation of the product (Jones et al., 2019). Consumers express a preference for simple and easy to understand labels (Van Kleef & Dagevos, 2015).

Numerous studies assessing the impact of nutrition labelling on consumers are available. The effect size found in these studies is largely dependent on the study design. The adolescents' perception of monochrome Guideline Daily Amounts (GDA) in comparison with the multiple traffic light GDA was studied by Babio et al. (2013). It was observed that when participants had a choice between classic products (not signed as "light") and those marked with different GDA systems, they chose products with significantly less total energy, sugar, saturated fat and salt pictured by the multiple-traffic-light GDA system than when they used the monochrome GDA system. The front-of-pack multiple-traffic-light system helped adolescents to differentiate between healthier and less healthy food. Franco-Arellano et al. (2020) examined the influence of different FOP labelling symbols (warning labels, health star rating and traffic light labelling) and nutrition claims (nutrient content claims) and health claims (disease risk reduction claims) on consumers' perceptions of product healthfulness and purchase intentions of healthier and less healthy drinks, when presented together on a label.

The authors demonstrated that the FOP labelling had a significantly stronger influence than the nutrition claims. In the case of less healthy products, the three different FOP labelling systems reduced consumers' perception of product healthfulness and purchase intentions, whereas in the case of healthier products, health star rating and traffic light labelling created a "halo" effect (tendency for positive impressions based on an idea or suggestion, not real data). On the other hand, such effects were not observed with warning labels, both in terms of consumers' perception of healthfulness and their purchase intentions (Franco-Arellano et al., 2020). The results were in agreement with a study by Lawrence et al. (2018) demonstrating the positive orientation of the Health Star Rating system for all food products with a star-based system. The authors also explained the benefit as a possible "halo" effect.

In a recent study, Pettigrew et al. (2023) investigated the relative ability of five different interpretive front-of-pack food labels to alert consumers to both healthier and unhealthier options. The authors concluded that the Nutri-Score performed best in assisting respondents with identifying the healthiest and least healthy options, followed by the health star and multiple traffic lights systems. The results indicated that the spectrum of FOP labels has utility in steering consumers away from unhealthier options and guiding them towards the healthier ones.

Ares et al. (2018) compared three interpretative schemes (Nutri-Score, Health Star Rating and nutritional warnings) in terms of their attentional capture, processing time, influence on perceived healthfulness and purchase intentions of products with different nutritional profiles. The attention to FOP labels and processing time were evaluated using a visual search task in which participants were presented with food packages. The Health Star Rating was found to perform worse than the other two schemes in terms of capturing attention and altering perceived healthfulness and purchase intentions. The authors pointed out that the Nutri-Score, which uses the traffic-light-colour system, may have contributed to capturing consumers' attention better than the other two schemes (Ares et al., 2018).

Angelino et al. (2019) evaluated the nutritional quality of breakfast cereals based on their nutritional values as declared on the labels. The results support the importance of nutritional education towards a better understanding of food labels as a key point to help the consumer in making healthy food choices.

Evidence suggests that healthier foods tend to be more sustainable (Potter et al., 2023). Studies using an environmental label identical in format to the Nutri-Score label have suggested that including both nutrition and environmental labels improved the nutritional but not the environmental outcomes compared to unlabelled conditions (De Bauw et al., 2021).

The controversies of the consumers' perspective on FOP labelling were discussed by Van Kleef & Dagevos (2015). The authors noted that FOP labelling is frequently advocated for changing unhealthy food habits; however, little empirical and consistent evidence exists to support this argument. Traditional consumer research approaches, based on self-reporting, are valuable but limited as consumers tend to give socially desirable answers. A more realistic understanding could be obtained by field experiments with actual food choices or search behaviours as key dependent variables to study how real-life shopping behaviour interacts with various environmental cues as well as personality characteristics (Van Kleef & Dagevos, 2015). There is a further need for more research studying consumers' use of nutritional information on food labels in a real-world setting.

9.3. Date labelling

Expiry dates are often considered as one of the most important elements of the label (Djekic & Smigic, 2016; Zielińska et al., 2020). The majority of consumers claim to check them, but some of them admit to have problems with finding the date on the packaging or consider date labels as unreadable (Samotyja, 2021), despite the fact that the labelling guidelines state that obligatory information shall not be hidden, obscured, detracted or interrupted by any other written or pictorial matter or any material. Unfortunately, still many consumers present low level of knowledge concerning the types of date labelling, which, in turn, increases the amount of food wasted. Moreover, they cannot correctly indicate which date type is typical for certain food products (D'Amato et al., 2023). A survey conducted in Poland has shown that almost half of the respondents do not see a difference between the phrases "use by" and "best before", and one in five respondents says that they have difficulty commenting on the issue (Zielińska et al., 2020). In the study led by Shamim et al. (2022) it was found that the "best before" date was the least understood one, as around 45% of Indian respondents either perceived its meaning wrongly as a "safety indicator" or were "not sure". Similarly, in the study by Zielińska et al. (2020), almost 40% of respondents indicated that the date of minimum durability ("best before") means the date after which the product becomes unsafe for the consumer (e.g., may cause poisoning), while only 9.8% consider that date as the date after which the product can be consumed.

According to Regulation (EU) No 1169/2011, the "date of minimum durability of a food" means the date until which the food retains its specific properties when properly stored. The correct interpretation assumes that food can be consumed past this date, although its quality may not be optimal. Laboratory tests of milk, pasta, mayonnaise and jam confirmed the microbiological safety of the products even six months after the "best before" date (Zielińska et al., 2020). In the case of foods which, from a microbiological point of view, are highly perishable and are therefore likely after a short period to constitute an immediate danger to human health, the date of minimum durability shall be replaced by the "use by" date (Regulation 1169/2011).

Many studies show that consumers find food products that exceed their "best before" dates as unsuitable for consumption (Neff et al., 2019; Samotyja & Sielicka-Różyńska, 2021; Shamim et al., 2022; Zielińska et al., 2020). Only a low percentage of consumers admit that they consume expired durable products. In the work of Samotyja and Sielicka-Różyńska (2021), 41% of participants rejected the "best before" labelled samples of rice, canned fruits, UHT milk, ready-to-eat sterilised soup one day passed the expiry date. McCarthy and Liu (2017) noticed inconsistency between attitudes and behaviours, as green consumers, including those who value organic food and vegetarianism, waste quite a lot of edible food. Quested and Luzecka (2014) found that households with children are more likely to throw food out past the date on its label and suggest that food safety could be the reason. However, in the study of Marklinder and Eriksson (2015), consumers kept refrigerated expired "best before" products, and only a small percentage of them assessed the products as being inedible.

Furthermore, the number of days left to the "best-before" date has a significant effect on stated edibility (Li et al., 2021; Marklinder & Eriksson, 2015; Samotyja and Sielicka-Różyńska, 2021; Sielicka-Różyńska & Samotyja, 2023). Consumers seem to reject samples even before the expiry day triggered by quality concerns or safety doubts (Ankiel & Samotyja, 2020). Passing the expiry date increases the level of rejection. Knowing that the sample has expired causes a decrease in the perceived attractiveness of the product and, in turn, determines negative expected liking. It was found that if consumer's perception of the food's attributes is impacted by expectations based on the "best before" date, the expired food is perceived to be of poor quality, even though it is not, and it might thus be discarded only for that reason (Sielicka-Różyńska & Samotyja, 2023). According to earlier findings, the presence of competing goals may also have an impact on the consumer's decision whether to consume or reject the food product. Food-handling practices might be influenced by motivational factors related to goals such as ensuring food safety.

In certain situations, these goals may conflict with the goal of reducing food waste, e.g., when consumers are faced with a decision whether to eat or throw away foods they are unsure of as to their edibility (van Geffen et al., 2020).

The decision whether or not to eat or discard a particular food item is greatly influenced by the food product category. In the study of Shamim et al. (2022), curd, pasteurised milk, bread and canned foods were the most frequently thrown away products. Slightly over 70% of the Polish respondents, who knew that the food could be safely consumed after passing the "best before" date, would discard the expired UHT milk, while canned fruit would be thrown away by 44% of the participants surveyed (Samotyja, 2022).

All the above-mentioned factors influence the decision concerning nearly or already expired "best before" products, and in turn impact the level of food waste (Figure 9.2).

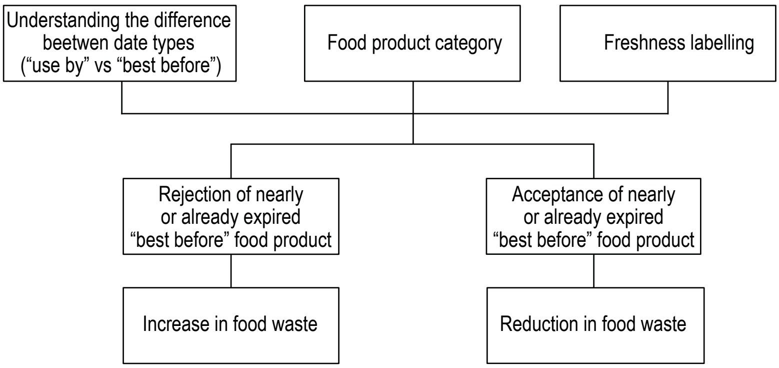

Figure 9.2. Date labelling factors influencing the decision concerning nearly or already expired "best before" food products
Source: own compilation.

9.4. Should the "best before" date go to the dustbin?

It has been proved that applicable legal regulations regarding date labelling are one of the factors affecting food waste during food turnover and in households. A European Commission study on date marking concluded that up to 10% of all food waste generated in the EU could be linked to date marking (European Commission, 2018). The main consequence of the present regulations is the need to withdraw from sale expired "use by" labelled foods, which is obviously justified (Regulation (EU) No 1169/2011). More controversy has arisen around the dates of minimum durability. Although the latest European regulation allows food business operators (FBOs) to redistribute expired "best before" food products, provided they are safe and properly handled (Commission Regulation (EU) 2021/382), in some countries they are not normally sold and are withdrawn from the shop shelves on the basis of local regulations. This not only promotes food waste but also misleads the consumer about safe consumption and the meaning of the "best before" date. Another controversial issue is whether the date was assigned in a reliable manner based on the results of scientific research, and it was not excessively limited and shortened to make products appear fresher (Eriksson et al., 2020). There is evidence that similar food products may have completely different expiration dates in different countries according to the retailer's requirements or manufacturer's choice or perception (Eriksson et al., 2020). This situation proves that manufacturers use subjective criteria, and in certain situations the assigned date may be longer. The use of the methodological approach at the stage of date establishing as well as considering the consumers' criteria and perception of food quality is an important factor affecting the level of food waste (Samotyja, 2016).

Opponents of giving up dates put forward an argument that the removal of the "best before" date from products might simply shift the responsibility for food waste from the retail to the household level. In Great Britain, where food can legally be sold after passing of the minimum durability date, some producers tend to shift from the "best before" date to the "use by" date in order to avoid a situation when a product of unsatisfactory quality falls into the hands of consumers as a result of being on the market for too long (FSA/DEFRA, 2011). The study by Sielicka-Różyńska and Samotyja (2023) exhibited that date labels may have an opposite contribution to consumers' apprehension of foods. On the one hand, they play a role in rejecting expired food by consumers, leading to an unfounded belief that the food's sensory attributes have been altered. On the other hand, it has been proved that "best before" dates maintain a consumer's positive attitude towards fresh products and reduce consumer uncertainty regarding food edibility, which would be experienced in the absence of date labels. In the light of this data, the resignation from the "best before" date does not seem to be a rational solution. In fact, more effort should be put in designing a new solution that will overcome consumers' lack of attention as well as in effective communication (D'Amato et al., 2023; Turvey et al., 2021). Consumers should also be educated in order to be able to recognise the sensory changes related to quality deterioration of safe products. Campaigns to familiarise customers with suboptimal food products should also be conducted. Suboptimal foods (SFs) encompass foods with the highest unfavourable sustainability-related impact that causes the largest amount of food waste. According to Aschemann-Witzel et al. (2015), SFs are food products with an abnormal appearance or other deviating product attributes (e.g., texture and smell) as well as products that are close to or have passed their expiration dates but are still unreservedly consumable. Retailers often discount these products to reduce in-store wastage, but research shows that proper, customised information to different consumers (focusing on savings or ethical reasons) might be more effective.

Conclusions

Globally, lack of education, ignorance and literacy result in poor and unsustainable treatment of food by consumers. Legal institutions such as the World Health Organization (WHO) and European Commission, together with scientists, try to define the principles of effective food policy actions in order to make smart food policies which would strategically target food preference formation, expression and reassessment in the broader context of environments and systems (Hawkes et al., 2015). Therefore, smart policies extend beyond making healthy choices the easy ones, aiming to make healthy choices the preferred ones. One of the elements of smart food policy is recommending the implementation of the front-of-pack (FOP) information and expiry dates to educate and guide consumers towards healthier and more sustainable food choices, as part of comprehensive strategies to prevent diet-related noncommunicable diseases and food waste. Nowadays, there are a few labelling systems around the world dedicated to give consumers specific information based on: endorsement logos (pictograms informing about the overall healthfulness of the product), nutrient specific warning labels (informing about the negative or positive influence of selected nutritional compounds), as well as interpretive nutrition rating systems (colour- or star-rating guides providing nutritional information about the product). It is a fact that different representations of the labelling systems result in more or less detailed nutrition information conveyed to the consumer. A more graphic representation often results in significantly less detailed information for the consumer. That is why one of the principles of effective food policy is educating consumers how to read the information on the packaging of the product (nutritional values, expiry dates—"use by" and "best before") on order to support healthier and more sustainable choices. Front-of-package labelling could be one of the measures to achieve the consumers' goal to make healthy and easy food choices. It is not (and cannot be) the only solution to prevent unsustainable treatment of food and the epidemic of diet-related noncommunicable diseases. However, FOP labelling can be part of a food policy intervention.

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10. SHAPING SUSTAINABLE FOOD CONSUMPTION ATTITUDES: BIBLIOMETRIC LITERATURE REVIEW

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Abstract

Sustainable food consumption is a crucial aspect of achieving a sustainable future. However, changing people's attitudes towards food can be a difficult task. In this article, we will conduct a bibliometric literature review to explore the current state of research on shaping sustainable food consumption attitudes. The study uses a sample of 922 papers in various bibliometric analyses. The authors use citation and collaboration analysis to determine the most significant authors and journals, and examine the relationships between the main authors and institutions. Next, they conduct content analysis, using bibliographic coupling, to determine the main areas of research within sustainable food consumption attitudes. The chapter attempts to identify the most important authors, journals and trends in each field.

Keywords: sustainable food consumption, consumer attitudes, bibliometric literature review, sustainability.

JEL codes: D12, Q01, Q18.

Introduction

Our planet's diverse and fragile life-support systems are under threat from global warming, which causes more severe and frequent weather disasters, lowers the variety of living species and challenges our existing lifestyles (Koide et al.,

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2021). The food consumed in households contributes to over 60% of the world's greenhouse gas emissions and uses up between 50 and 80% of the total resources (Poore & Nemecek, 2018). Therefore, it is increasingly important to make consumer dietary habits more compatible with environmental sustainability (Roh et al., 2022). Especially in wealthy countries, changing food consumption is seen as a key requirement for achieving global sustainability goals (Balvanera et al., 2022).

Making decisions related to food is complex and influenced by various social, cognitive, emotional and environmental factors (Leng et al., 2017). The significance of food preferences, choices and habits in human cultures is substantial, extending beyond the basic need for survival (Enriquez & Archila-Godinez, 2022). Additionally, food choices are influenced by marketing strategies employed by food companies, which have impacted dietary norms, population-level preferences for specific food and drink categories, and the cultural values associated with food behaviours (Hemmerling et al., 2015). Shaping sustainable food consumption (SFC) attitudes is a challenging task due to their integral role in people's lifestyles and the sociocultural environment they are part of (Köster, 2009). Therefore, efforts to promote SFC environmentally face competition from other contextual influences on people's food choices.

The aim of the study is to analyse the current state of knowledge and to indicate future directions of research on shaping SFC attitudes. To meet this challenge, a bibliometric literature review was conducted. The scientific database Scopus was used as the data source. A sample of several hundred articles obtained in this way was analysed using the Biblioshiny—Bibliometrix and VOSviewer applications. The formulated research questions concern the identification of the leading authors of the research and their countries of nationality, as well as getting to know the most important journals and future research directions:

1. Who are the leading authors of research on shaping SFC attitudes?
2. What is the nationality of the leading authors of research on shaping SFC attitudes?
3. What are the most important magazines that publish articles on shaping SFC attitudes?
4. What are the main directions of future research on shaping SFC attitudes?

10.1. Definition of shaping sustainable food consumption

In the literature on the subject, there is no single definition of sustainable food consumption (SFC) that would be common to all researchers (Kamenidou et al., 2019; Lorenz & Langen, 2018; Thøgersen, 2017). The richness of terminology results to a large extent from the existence of many currents of chemical, biological, psychological and economic research. Although the general characteristics of SFC are perceived in a similar way by most authors, it can be noticed that almost all of them define these characteristics in a different way—appropriate to a certain area of science (Annunziata & Scarpato, 2014; Kamenidou et al., 2019). In order to carry out a bibliometric review, the subject scope of SFC, adopted for the purposes of this work, in accordance with FAO (FAO, 2010), should be approximated.

SFC is a category that includes the choice of environmentally friendly food (including organic food) (Scalvedi & Saba, 2018; Vittersø & Tangeland, 2015), animal welfare (Lorenz & Langen, 2018; Miranda-de la Lama et al., 2018) and fair trade (Clarke et al., 2007). This concept has entered a broader context of theoretical explanations of human behaviour by linking it to various dimensions of consumption, which include reducing the consumption of meat and processed products (Clonan et al., 2015; Vainio et al., 2016), increasing the consumption of fruit and vegetables, as well as consuming products that have a lower carbon footprint (Hartikainen et al., 2014). SFC has also become a core category in empirical studies relating to the consumption of locally produced food (Feldmann & Hamm, 2015; Scalvedi & Saba, 2018). Furthermore, some scientific reports refer to the behaviour of buyers related to waste management, including not wasting food (Lorenz & Langen, 2018; Song et al., 2015). Among the ranges of contemporary definitions of SFC, such aspects as attitudes, perceptions and other aspects of consumer behaviour are also indicated (Salazar et al., 2013; Wang et al., 2014), pointing to the influence of social norms (De Maya et al., 2011; Richter & Klöckner, 2017) or profiling the green consumer (Akehurst et al., 2012).

10.2. Description of the method and procedure for data acquisition

The conducted research was guided by the indications of Zupic and Čater (2015), who suggest that the process of bibliometric analysis should include a number of stages, such as research planning, bibliometric data collection, analysis (including data cleaning), visual presentation and interpretation of the results (Kryszak et al., 2021).

Bibliometric analysis provides an advantage over a systematic review (Fan et al., 2022; Lim et al., 2022) by providing the productivity and impact of existing research and exploring major themes and patterns of collaboration (Mukherjee et al., 2022).

Scopus database was used for the analysis. It is a multidisciplinary bibliographic and citation database that contains abstracts and references of scientific articles, conferences, books and patents in various fields. The choice was also guided by the greater complexity of this database, compared to Web of Science (WoS) (Levine-Clark & Gil, 2009). At the same time, the scope of Scopus is wider than that of WoS, as it includes journals with good citations that are usually ignored by WoS (Vieira & Gomes, 2009). Another database that can provide greater depth of information is Google Scholar (Franceschet, 2010), but it does not provide data ready for analysis and includes many journals of purely local interest, as well as duplicate records (Mingers & Leydesdorff, 2015).

In order to find all relevant documents, we used the following expression: (attitude* AND food* AND (ecolog* OR green OR sustainab*)* AND (consumer OR consumption)*). The search was based on "title, abstract, keywords". In order to ensure coverage of related publications, the "OR" logical operator was used to combine all combinations. Figure 10.1 shows a graphical view of searching for data by the "title, abstract and keywords".

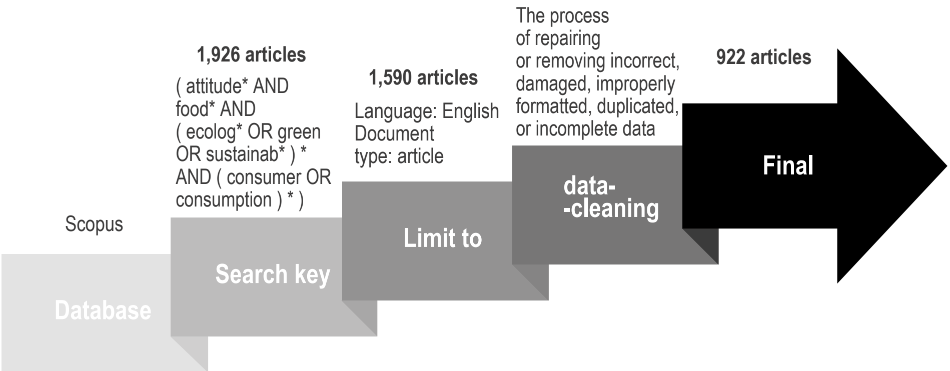

Figure 10.1. The process of obtaining data for analysis
Source: own compilation.

After the initial search, 1,926 documents were obtained. However, in the next step, only research articles published in English were left. At that time, 1590 articles remained. Bibliometric methods depend to a large extent on the quality of data, so the next step was to clean the database. Data cleaning and disambiguation is a necessary and time-consuming process (Besselaar & Sandström, 2016).

To clear the data, we applied the following main rules:

- an article had to comply with the definition of SFC chosen during the literature review (overly broad research scope was excluded),
- an article was rejected if it was incomplete, badly formatted or duplicated,
- articles related to sustainable consumption in the field of medicine and agriculture were excluded,
- selected articles focused on human food (animal food articles were excluded).

After eliminating irrelevant papers, removing any articles not directly related to the research topic, as well as corrupted, incorrectly formatted, duplicate or incomplete data, a sample of 922 articles was obtained and used for the analysis.

The following programs were used for the analysis: Bibliometrix and Biblioshiny in the RStudio as well as VOSviewer.

10.3. Results

Table 10.1 presents the main structure of the collected data. Publications cover the years 1994–2022 and consist of 922 articles published in 309 journals, written by 2,919 authors. Only 59 articles are attributed to individual authors, which confirms the general trend of cooperation also in the field of SFC. The average citation rate is relatively high, at around 34 citations per article, indicating a growing influence and interest in this field of research.

Table 10.1. Main information on the topic of SFC

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	1994–2022
Sources (journals, books, etc.)	309
Documents	922
Annual growth rate %	20.52
Documents' average age	4.78
Average citations per doc	34.45
References	52656
DOCUMENT CONTENTS	
Keywords plus (ID)	3056
Author's keywords (DE)	2559
AUTHORS	
Authors	2919
Authors of single-authored documents	59
AUTHORS' COLLABORATION	
Single-authored documents	65
Co-authors per document	3.76
International co-authorships %	26.25
DOCUMENT TYPES	
Article	922

Source: own compilation.

Figure 10.2 shows the development of published articles on SFC. Since 2018, there has been a clear upward trend in which the number of articles on SFC is definitely growing. This tendency suggests that this topic has become an important and relevant issue in scientific and social discussions.

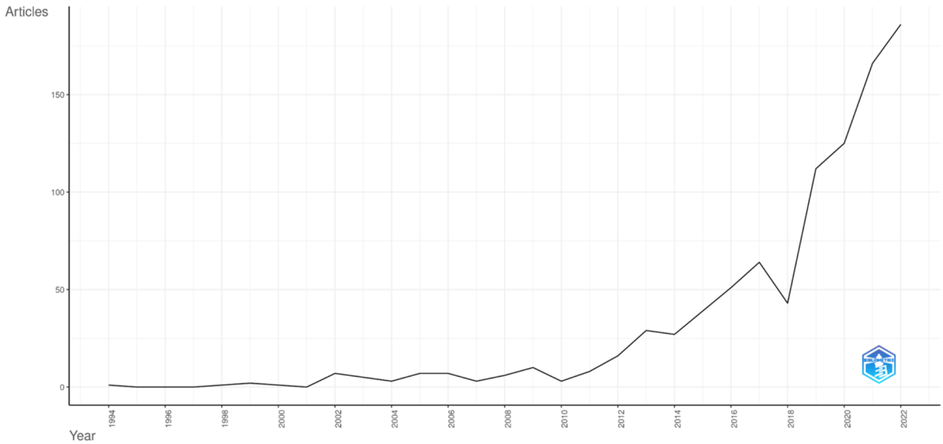

Figure 10.2. Number of publications on the SFC topic from 1994 to 2022
Source: own compilation.

The surge in publications reflects increased public interest in SFC issues. This phenomenon can be the result of many factors. Growing ecological awareness and care for the environment, changing consumer preferences as well as technological and scientific progress are just some of the possible reasons for the increased interest in the subject.

Table 10.2 shows ten scientific journals that have published the most articles on SFC. *Sustainability* is in the first place with 92 published articles, followed by *Appetite* with 71 articles and *British Food Journal* with 61 articles.

Table 10.2. Sources with the most published articles

Sources	Articles
Sustainability (Switzerland)	92
Appetite	71
British Food Journal	61
Journal of Cleaner Production	37
International Journal of Environmental Research and Public Health	35
Nutrients	27
Food Quality and Preference	23
Foods	21
PLoS ONE	20
Food Research International	18

Source: own compilation.

Table 10.3 shows countries in which the research topic in question was most often covered in scientific articles. Italy is in first place with 404 publications, the USA is in second place with 334 publications and China is in third place with 273 publications.

Table 10.3. Countries with the highest number of published articles on the research topic

Region	Articles
Italy	404
USA	334
China	273
UK	226
Germany	196
Australia	139
Brazil	126
Spain	120
Netherlands	117
Poland	92

Source: own compilation.

The following places belong to: Great Britain with 226 publications, Germany with 196 publications, Australia with 139 publications, Brazil with 126 publications, Spain with 120 publications, the Netherlands with 117 publications and Poland with 92 publications. The analysis of this table shows that research on SFC has been conducted on a large scale in various countries around the world. Italy, the USA and China stand out as the countries with the most articles published on this topic. This is a sign of global interest in the issues of SFC and its impact on the environment.

Countries where the research topic has been published in scientific articles are shown in Figure 10.3. It is worth noting that the list includes both countries with

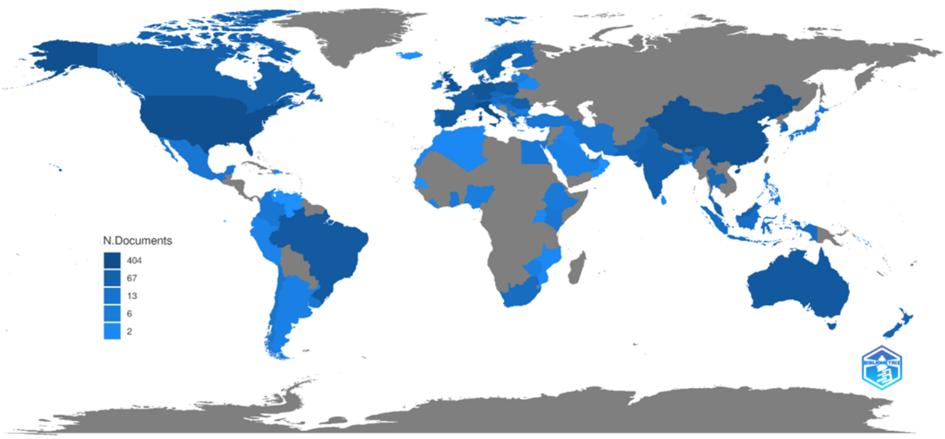

Figure 10.3. Countries where the research topic has been published in scientific articles
Source: own compilation.

large global economies and smaller countries, which shows that SFC is a research topic of international importance.

Table 10.4 shows ten authors with the most published papers on SFC. Verbeke is in first place with 11 published articles and Spiller is in second place with 9 articles. The listed authors are important researchers in the field of SFC, contributing to the scientific literature on the subject. The number of papers published by these authors shows their commitment to research into sustainable nutrition and the impact of consumption on social and ecological aspects. It is worth noting that the table reflects the diversity of the authors, both in terms of their nationality and research fields. This proves the international nature of research on SFC and the involvement of many scientists from different countries and specialisations.

Table 10.4. Top ten authors according to the number of published documents about SFC

Authors	Articles	Fractionalized frequency*
W. Verbeke	11	3.95
A. Spiller	9	3.25
M. Siegrist	7	2.33
H. S. Chen	6	3.08
S. Hercberg	6	1.04
A. Krystallis	6	1.77
A. Annunziata	5	2.50
Q. Chen	5	0.69
J. De Boer	5	2.00
K. G. Grunert	5	1.02

* The fractionalized frequency quantifies the individual contribution of each author by assuming equal shares among all co-authors of the affiliated papers.

Source: own compilation.

10.4. Bibliography coupling and content analysis

To identify articles on a given topic that are most cited and impactful, the time range of the analysis was shortened to the last five years. This avoids a situation where a much older article would have more citations than a newer one. Limiting the analysis to the last five years allows more accurate identification of the latest and most important publications in a given field. This, in turn, facilitates the understanding of current trends and research approaches in a given field, which is important for further scientific work and research.

The main purpose of using bibliographic coupling is to clarify the dimensions and streams of literature in a given research field (Chiaramonte et al., 2023). Figure 10.4 shows the results of our bibliographic linkage analysis, using colours to distinguish streams in the SFC literature.

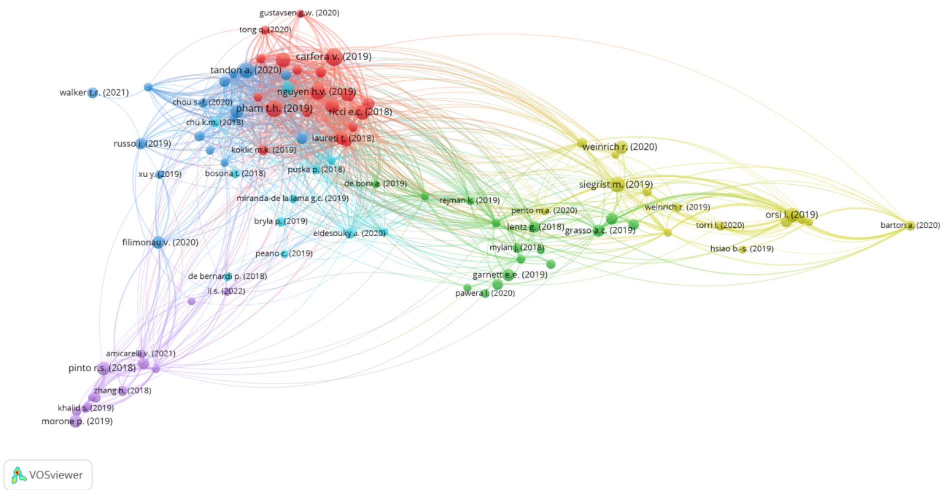

Figure 10.4. Visualisation of most cited articles

Source: own compilation.

Six streams have been identified in a sample of 922 papers that exceed 30 citations (Chiaramonte et al., 2023; Khan et al., 2020) to guide future research directions.

10.5. Setting future research directions

The use of both bibliometric analysis and content analysis allows us to detect possible gaps in scientific research and determine future research directions. Table 10.5 presents a summary of the future research agenda for each research stream, based on three most cited documents within each stream.

Table 10.5. Future research agenda

Cluster No	Author and year of publication	Aim of article	Directions of future research
1	Nguyen et al. (2019)	The aim of this article is to identify the influence of personal factors (care, knowledge, etc) and contextual and environmental factors on consumer decisions regarding the purchase of organic food.	The future direction of research results from the limitations of the research sample (especially comparative analysis of rural versus local). In additional, it is suggested to explore the interconnectedness of determinants of consumer attitudes towards organic food to further address the motivational complexity of organic food consumption. Furthermore, the authors suggest focusing on changes in attitudes and behaviour over time.

Table 10.5 – cont.

Cluster No	Author and year of publication	Aim of article	Directions of future research
1	Carfora et al. (2019)	The aim of this article is to investigate, from a psychological perspective, the elements (determinants) that can predict attitudes to and purchases of organic products (organic milk). The study is based on the Theory of Planned Behaviour, which was extended to include trust in the supply chain actors and self-identity of the consumers in question as "green consumers".	Future research could control the role of other important consumer predispositions. The authors suggest focusing on affective components, utilitarian versus hedonic aspects, self-efficacy in eating and performance intentions, especially based on the context of pro-health and pro-environmental activities.
	Pham et al. (2018)	The aim of this article is to investigate how different factors may enhance or impede young consumers' intentions to purchase a specific type of eco-friendly product. The authors focus on factors such as: health consciousness, media exposure, consumers' environmental concern and food taste perceived barriers (i.e. high price, inadequate availability, poor labelling and extra time required).	It is suggested to examine changes in consumer attitudes and identify how their intentions turn into reality in purchasing behaviour. Given the complexity of consumer behaviour towards organic products, future research may also test modified models that take into account interconnections between the previous ones, such as between media exposure and food safety concerns. Additionally, some moderating factors, such as past behaviour, knowledge, gender and income, can be examined. Finally, there is also a need for a comparative study of organic food purchases and consumption in both developed and developing countries.
2	Garnett et al. (2019)	The aim of this article is to examine the impact of attempting to nudge meal selection by increasing the proportion of vegetarian meals.	Future research could replicate the study using another sample. The authors suggest focusing on low- and middle-income groups, other countries and availability of meat-free choices.
	Grasso et al. (2019)	The aim of this article is to investigate the readiness of older consumers to accept the consumption of the following sources of alternative, more sustainable protein: plant-based protein, insects, single-cell protein and in vitro meat. The authors focus on the associations of different food-related attitudes and behaviours as well as socio-demographics with older consumers' acceptance to consume protein from such sources.	Future research could identify the impact of other possible determinants of acceptance of eating sustainable sources of protein, such as familiarity, social norms, awareness, perceived consumer effectiveness and perceived product availability. In addition, the authors suggest conducting studies in which sustainable food choices are put in context by providing pictures of meals or products, or real products, i.e. insects or insect-based protein as an added ingredient.
	Lentz et al. (2018)	The aim of this article is to identify potential drivers for the reduction of meat consumption. Based on the Theory of Planned Behaviour (TPB) and the Meat-Attachment Questionnaire (MAQ), this study investigated consumers' attitudes, motivations and behaviours in regard to meat consumption.	Future research directions are very embedded in the limitations of the research, i.e. its methods and scopes (measuring meat consumption accurately with "consumption diaries"). In addition, it is suggested to examine the changes in attitudes. The authors suggest focusing on interventions and media campaigns, which can imitate these changes.

Table 10.5 – cont.

Cluster No	Author and year of publication	Aim of article	Directions of future research
3	Tandon et al. (2020)	The aim of this article is to examine consumers' motivations for purchasing organic food and to explore the relationship between motivation, attitude and buying behaviour. Using the self-determination theory, the study addresses the knowledge gap regarding the factors driving the actual consumption of organic food, particularly in emerging economies.	The authors suggest conducting cross-cultural studies to investigate whether and how cultural differences affect the consumption of organic food. They suggest similar research among consumers living in smaller cities and semi-urban regions. Future research should focus on evaluating legal policy and government support for the marketing and production of organic food.
	Woo & Kim (2018)	The aim of this article is to apply the multidimensional concept of perceived value (GPV) in the context of purchasing eco-friendly food products in order to better understand consumer behavioural intentions and explain the formation of purchase intentions for these products. The study examines the relationships between GPV, consumer attitudes and purchase intentions.	Future research could replicate the study using a probabilistic sampling frame. Moreover, it was noticed that consumers' attitudes and intentions do not always reflect their actual purchasing behaviour. Therefore, future research should focus on examining the actual purchasing behaviour through observation or interviews.
	Filimonau et al. (2020)	The aim of this article is to examine factors influencing consumer engagement in reducing food waste in restaurants in Poland and to provide recommendations for policies and management practices that strengthen consumers' intentions and pro-environmental behaviours in this area.	There is a need for more detailed research on the factors determining consumer involvement in reducing food waste in restaurants, both in Poland and in other consumer markets, preferably by developing, testing and validating dedicated measurement scales.
4	Orsi et al. (2019)	The aim of the article is to investigate perspectives and factors determining the acceptance of insect consumption as a food source in Germany, with a particular focus on processed insect products.	The authors suggest conducting representative studies that use methods other than online questionnaires. Future research should focus on observing the actual insect-eating intentions and behaviours rather than rely solely on self-reported willingness. In addition, qualitative research, taking into account a wider range of attributes and analysis of long-term or panel data, could better contribute to understanding the dynamics of insect food acceptance in European markets.
	Siegrist & Hartmann (2019)	The aim of the article is to examine how consumers perceive the environmental impact of different foods, specifically meat substitutes and organic meat, and to determine the factors influencing their consumption choices. The study also highlights the importance of consumer knowledge regarding the environmental impact of food in promoting more SFC.	The text highlights the need for further research to better understand the impact of meat substitute consumption on the amount of meat consumed and the role of environmental and health motives in making sustainable food choices. The authors encourage further research into the relationship between consumers' knowledge of sustainable nutrition and their eating behaviour, as well as the development of measurement scales that measure consumers' knowledge of the environmental impact of different food products.

Table 10.5 – cont.

Cluster No	Author and year of publication	Aim of article	Directions of future research
4	Weinrich & Elshiewy (2019)	This article aims to analyse consumer preferences for microalgae-based meat substitutes as a sustainable alternative to traditional meat consumption, addressing environmental concerns and health issues.	Future research in food engineering and sensory marketing is needed to understand consumer preferences for microalgae-based meat substitutes.
5	Pinto et al. (2018)	The aim of this article is to demonstrate how a simple and inexpensive educational campaign can effectively reduce food waste in university canteens by raising awareness and suggesting actionable steps, highlighting the importance of collaboration between canteen staff and students for long-term sustainability.	It is suggested that further and future research on the relationship between plate waste and the dining atmosphere is needed to clarify this relationship as it is not the focus of this article.
	Fami et al. (2019)	The aim of this article is to examine the relationship between food consumption management and food waste in households in Tehran, Iran, with a specific focus on women. The article aims to develop a model and identify key factors influencing food waste, considering the socio-economic and environmental consequences as well as the need for a sustainable food waste prevention plan.	This study was aimed at people who took care of home meal planning and preparation. Some error may have occurred in the study resulting from the fact that the person responsible for the household may have been more or less aware of food planning and waste control. Therefore, it is advisable to adopt arrangements from other countries and draw on the experience of local and international communities. In order to better understand the behavioural intentions of households in the food waste reduction program, the authors recommend that a more detailed study be carried out locally, and the data collected can be carried out more efficiently and extensively with the support of the government.
	Morone et al. (2019)	This article aims to identify effective policy actions and private initiatives that can change the current unsustainable food consumption model in high-income countries to significantly reduce food waste. The results provide valuable information for policymakers and contribute to filling the knowledge gap regarding policy strategies to combat food waste.	Assessing the effectiveness and impact of different public food waste legislation and private initiatives in different contexts and regions using common frameworks and indicators. Investigating the barriers and drivers for adopting and upscaling biorefining technologies and practices, and their implications for food security, nutrition and environmental sustainability. Developing and testing innovative approaches and tools to raise awareness and change consumer behaviour towards more SFC patterns, taking into account cultural, social and psychological factors. Assess trade-offs and synergies between food waste reduction/valorisation and other policy objectives such as climate change mitigation, biodiversity protection, circular economy and social justice.

Table 10.5 – cont.

Cluster No	Author and year of publication	Aim of article	Directions of future research
6	Watanabe et al. (2020)	The aim of this article is to investigate the impact of perceived value on consumers' trust and purchase intention in the Brazilian organic food market, thereby enhancing our understanding of consumer behaviour in this context.	Despite the diligence and methodological meticulousness adopted in conducting the research, it has some limitations: first, a non-probability convenient sampling technique, which makes it impossible to generalise the results. Regarding this limitation, the sample focused on younger consumers from one Brazilian metropolitan city. Therefore, a more heterogeneous sample can be targeted for future research to determine the stability of the observed results. The predictors of consumers' purchase intention and trust may also be explored in further research, including, for example, health issues. In addition, the direct relationship between trust and purchase intention could also be deepened in other studies, as this relationship has not been not confirmed in this study.
	Eldesouky et al. (2019)	The aim of the article is to investigate consumers' perceptions and attitudes towards environmental labels on food products and their impact on purchasing decisions.	Research on different types of food products marked with "sustainable" labels.
	Bryła (2019)	The goal of the article is to assess the level and predictors of regional ethnocentrism on the market of regional food products in the context of sustainable consumption, thus contributing to the understanding of consumer ethnocentrism by exploring its regional dimension and its relation to sustainable development.	Future research may address the phenomenon of regional ethnocentrism in other countries and in relation to other categories of products and services. The phenomenon of regional ethnocentrism can be studied in an experimental setting using real or fictitious brands associated with different regions. The role of text references to the region of origin on the product packaging can be compared to visual stimuli with the same purpose, such as logos, pictures, maps or symbols. Eye tracking can be used to investigate the attention given to the region of origin information on packaging.

Source: own elaboration.

Conclusions

In this chapter, we examine the bibliometric features of the literature on SFC. Focusing on the period 1994–2022, we have found 922 papers involving 2,919 authors, which allowed us to detail the state of the art in the field and future research opportunities.

Interest in SFC has increased in recent years. Data analysis shows an increase in the number of publications on this subject, which proves the growing environmental awareness and changing consumer preferences. In total, 922 articles published in 309 journals by 2,919 authors were collected. Many of these authors have collaborated, which reflects the trend of collaboration in the research on this topic. Italy, the USA and China are countries with the most articles on SFC. The research is conducted on a large scale, both in countries with large global economies and smaller countries. It is worth noting that many authors from different nationalities and research fields are involved in the research on this topic, which underlines the international importance of SFC. The leading scientific journal in the field of SFC is *Sustainability*, which has published the most articles (92). Among the authors who have made a significant contribution to the study of SFC, the most distinguished ones are: Verbeke, Spiller and Siegrist.

Last but not least, another contribution of this article is the agenda for future research, developed on the basis of cluster analysis. It is indicated that identifying the determinants of SFC (including, e.g., factors resulting from health problems of an individual or consumer knowledge and/or awareness of organic food), as well as the links between these factors, should be given more attention in the future.

Furthermore, more discussion should also be conducted on the actual purchasing behaviour of consumers in order to understand whether their attitudes and intentions are in line with the actual purchasing decisions (attitude-behaviour gap). Staying within the issue of attitudes towards SFC, the need to examine changes in consumer attitudes over time is indicated, including interventions that cause these changes.

Subsequently, due to the constant increase in food waste, it becomes important to develop a scale for measuring this phenomenon and factors that could build consumer involvement in the process of reducing food waste. An equally important issue is biorefining, which is a key pillar of the bioeconomy.

The last direction of future research, extending its subject scope, is the assessment of legal policy and government support for marketing activities and production of organic food, because it is legal regulations that largely regulate consumer awareness of sustainable development.

The authors of the analysed works also emphasise that their research is characterised by limitations resulting from the subjective scopes. They indicate that efforts should be made to eliminate narrow subjective scopes in order to conduct research on a representative group of recipients (e.g., extending research to include rural residents or citizens of other countries).

There are some limitations to the performed bibliometric analysis. The first one is the analysis of articles from the Scopus database, which does not include all scientific journals. It should also be remembered that this database may contain errors, as the items contained therein are not created for bibliometric analysis and may contain repetitions, for instance. It is indicated that future bibliometric research could be based on another database, such as the Web of Science, or on triangulation of several databases. The second research limitation is related to the nomenclature of clusters and the interpretation of future research directions, which remain biased because they depend on the subjectivity of the authors of the analysis.

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11. HOUSEHOLD FOOD WASTE—THE ORIGIN, LEVEL, STRUCTURE AND METHODS OF PREVENTION

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Abstract

Food waste is one of the major problems that humanity needs to solve. The gargantuan amount of food wasted each year, estimated at around 1 billion tonnes, creates a range of environmental, economic and ethical problems. Unfortunately, food is wasted to the greatest extent by households. To a lesser extent, food is wasted by producers or intermediaries. Therefore, the aim of this article is first and foremost to identify the causes of food waste by households. To do this, a conceptual framework has been adopted. It assumes that household food waste originates in three predictable stages—when shopping, storing and serving. In other words, households waste food because they do not prepare the food they purchase, they do not serve the food they prepare, and they do not consume the food they serve. The considerations in the paper are based on the available literature and secondary data.

Keywords: food waste, household, food waste data.

JEL codes: D10, D11.

Introduction

People waste food. One can even say that food wasting seems to be an everyday activity of our existence. It is the reality, regardless of whether we act as household members, company employers and employees or farmers. We waste food along the entire value chain—at the stage of food production, transportation, storage, processing, retailing and consumption (Hermanussen et al., 2022). What is more, some of us do not think food waste is a big issue since food is natural and biodegradable (Wiliams et al., 2012).

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The Food and Agriculture Organization of the United Nations (FAO) estimates that about a third of all food produced in the world is not consumed and is lost as waste without any specific utilisation. Interestingly, it does not matter how developed a given country is—food is wasted by those who live in developed as well as developing countries (Gustavsson et al., 2011).

Food waste is a huge issue as food loss and waste matter in terms of the environment, economy, food security and ethics (Flanagan et al., 2019). In terms of the environment, food loss and waste are responsible for an estimated 8% of annual greenhouse gas emissions. If the total amount of wasted food was taken as a "separate country", it would be the third largest producer of greenhouse gases after China and the United States. In fact, food waste generates more than four times the annual greenhouse gas emissions produced by the aviation industry. Researchers warn that excessive waste can also have serious effects on the changes in climate. They estimate that about ten percent of greenhouse gases are produced by decomposing food in waste dumps. However, the ecological problems do not stop here. Food waste also consumes a quarter of all water used by agriculture each year and requires an agricultural area the size of China to grow food that ultimately is not eaten by people (Flanagan et al., 2019). It also leads to a high degree of eutrophication of water bodies, causing impairment of biodiversity.

It also has to be highlighted that the food wasted by consumers and at food institutions has a higher accumulated environmental impact than the food wasted in the distribution chain, and is therefore even more important to be reduced (Wiliams et al., 2012).

In terms of the economy, at a global level, the annual market value of food that is lost and wasted is estimated to be an astounding $940 billion. In terms of food security as well as ethics, more than 1 billion metric tons of food is lost and wasted per year in a world where, paradoxically, a large number of people suffer from hunger. These people live mostly in developing and underdeveloped countries. According to the UN, almost 700 million people living on Earth have been suffering because of hunger and another three billion people do not have access to sufficient quality food and healthy diets.

What is worse, all these above-mentioned problems are just estimations as we still lack a proper way to precisely calculate the amount of food that is wasted every year. This is due to the fact that widely accepted definitions and methodologies to analyse food waste are still missing (Koester et al., 2018).

As a result of all the presented issues, the food waste dynamics seems to be a serious challenge both for developed and developing countries. The problem is not only the process of food waste generation but also the process of food waste management and food waste utilisation. There is no efficient and relevant food waste recirculation approach applied. The increasing food waste volume is becoming a challenge and is heavily discussed in the USA, European Union and many other countries.

Available data suggests that most food is wasted within households. According to the FAO, approximately 14% of food produced globally is degraded before it is sold and about 17% of the total food volume is lost at the level of individual households (final food consumers). If this food waste was loaded into trucks (40 tons capacity), their number could wrap around the planet seven times. Furthermore, other data provided by the United Nations (UNEP Food Waste Index Report, 2021) corroborate the same facts: the majority of food waste is generated at the level of households (as their food waste volume is estimated to be around 74 kilograms per person per year)—over 61% of the total food waste volume (households often buy more than they are actually able to consume). On the other hand, food waste generated by catering and food distribution services (mainly shops in retail) accounts for 32% and 15%, respectively. These percentages correspond to the following absolute values: households waste 569 million tons of food a year, food service: 244 million tones, and the retail sector: 118 million tones. Together, this adds up to an appalling almost 1,000 (931) million tones (1 billion tones) of food wasted annually. Other data show that in the EU alone almost 100 (88) million tons of food waste are generated annually, which is equal to 174 kg food wasted per average EU citizen, 143 billion euros lost a year and 170 million tons of CO_2 emitted to the atmosphere (Stenmarck et al., 2016). The list of available data on food waste goes on, painting a very pessimistic picture of human activity regarding food.

As was mentioned above, households are responsible for the largest amount of food waste along the entire value chain. Therefore, the aim of this article is to investigate the origin, level and structure as well as ways of preventing food waste.

11.1. Reasons for household food waste

According to a definition, households "waste food", which is a very important statement as food can also be lost. To make a clear distinction between these two terms, one must provide definitions of both of them. Thus, "food waste" occurs at the end of the value chain, at the level of household consumption, whereas "food lost" occurs at previous stages of the supply chain, that is production, processing, distribution, etc. (Food and Agriculture Organization, 1981). The term "food waste" unambiguously identifies the entity that is the source of this phenomenon—the final consumer, which is not only the household but also canteens and restaurants (Hermanussen et al., 2022). However, this paper focuses mainly on households.

Food waste can be classified into different categories based on the degree to which it can be prevented: unavoidable waste, potentially preventable waste (facultative avoidable), and preventable waste (avoidable) (Parfitt et al., 2010). Unavoidable waste is produced during food preparation and relates to inedible components such as bones, shells, coffee grounds, etc. Facultative avoidable waste occurs due to different consumer habits, such as peeling apples before consumption or not eating bread crust. Avoidable waste relates to food that is perfectly edible at the time of being wasted or that would be usable if it had been processed in time (Hermanussen et al., 2022).

Numerous studies have demonstrated that household food waste behaviour is influenced by various factors and interdependencies (BCFN, 2012; Gustavsson et al., 2011; Szymkowiak et al., 2022). To analyse food waste in a more systematic way, a conceptual framework will be adopted. It is based on the assumption that household food waste originates in three predictable stages—shopping, storing and serving (Wansink, 2018). Food waste occurs because households cook, prepare and serve more food than they can consume. That is, food can be purchased and never prepared, prepared and never served, or served and never eaten (Chandon & Wansink, 2012). In other words, the framework can provide an insight into why household members buy food they never prepare (cabinet castaways), why they prepare food they never serve (leftovers), and why they serve themselves food they throw away (plate waste) (Wansink, 2018).

Regardless of which stage of food waste is taken into consideration, there are a few fundamental reasons for food waste. Some of them are much more psychological in nature than economical. One such explanation is provided by the CAN concept. Within the framework of the CAN (Convenient, Attractive, Normal) model (Wansink, 2015), the ease of engaging in food waste depends on the perception of food waste reduction as a lack of convenience, attractiveness or normality. In other words, consumers waste food at all stages because saving food involves a lot of problems, more effort and time (related to, e.g., planning meals and purchases, storing food properly). Another psychological reason lies in the fact that in most cases food is not perceived as something valuable, and, as such, it is not worth minimising its wastage. This phenomenon can be explained by the "three A's" framework, comprising affordability, availability and attractiveness (Wansink, 2014), which offers three explanations. First of all, food has become more affordable than ever before—one research indicates that buying enough food is a financial struggle for only about 25% of consumers (wrap, 2022b). Secondly, food has also become increasingly available (in grocery stores), and, finally, it is more appealing (with multiple flavours of the same brand). To sum up, psychological explanations state that wasting food (that is not perceived as something valuable) seems to be easier than engaging in a cumbersome process of food preservation.

11.2. Stage I: Food is bought but not prepared

The most obvious answer to the question of why consumers buy food that is never uses is a massive marketing activity of both food producers and retailers. This activity has frequently been criticised for enticing consumers to purchase unnecessary products that may go unused, resulting in waste. One common accusation is that marketing creates or amplifies an artificial need (Lang & Heasman, 2015). Other allegations focus on how various elements of the marketing activity, such as merchandising, make it overly convenient for individuals to select products they do not actually need, or how pricing strategies like multipacks or buy-one-get-one-free offers make products appear as scarce bargains. Additionally, simple modifications or extensions of product flavours, or line extensions, can make them more appealing and combat boredom or burnout. These products are supported by marketing budgets that can lead consumers to stockpile more than they actually need. Moreover, sales promotions associated with these products can encourage individuals to try a product even when they are unsure if their family will like it (Wansik, 2018).

Marketing strategies of food producers influence waste also by the labelling conventions used for food products. The use of expiration dates, “use by” labels or “best purchased by” labels, psychologically extends the perceived time window during which a person believes they can consume the product before having to discard it. The further the date, the more optimistic individuals may be that they will find an opportunity to prepare and consume the food. However, at this stage of the food waste framework one needs to distinguish between perishable food and shelf-stable food, as the reasons for not using either one can vary considerably.

When it comes to perishable food items, especially produce, meat and dairy, the decision to discard them often stems from safety concerns regarding spoilage and potential for illness. Foods that exhibit signs of spoilage, such as smelly milk, grey-looking meat and liquefying lettuce, are often discarded. Jörissen et al. (2015) identified some reasons for food wastage by Italian and German consumers in their studies, including mouldiness, inappropriate taste/smell of the products and exceeding the “use by” date/date of minimum shelf life. Additionally, in Polish (Tomaszewska et al., 2020) and Finnish (Silvennoinen et al., 2014) households, food spoilage was found to be the cause of wastage of 65% and 29% of food, respectively. For dairy products and grains, the introduction of the expiration date labels (“use by” or “best before”) has provided consumers with seemingly objective criteria to either discard the expired products or consume them at their own risk (Graham-Rowe et al., 2014; Qi & Roe, 2016). However, research shows that, on average, consumers treat both “use by” and “best before” date labels similarly when it comes to disposal decisions for milk and yogurt. These findings suggest that there exists a notable portion of the population lacking comprehension regarding the distinction between the two categories of date labelling. Alternatively, even if individuals possess an understanding of the dissimilarity, they nevertheless exhibit a tendency to employ them in an interchangeable manner (wrap, 2023).

On the other hand, the reasons for wasting shell-stable food are a bit different as they are not strictly related to the food itself but rather to the motivation behind a purchase. According to research, this type of food is bought but never prepared because the products were purchased for a recipe that has never been prepared, or they were purchased for a specific purpose or special occasion that has never transpired. When commenting on the results, one can also point out the psychological reasons for food waste, i.e. consumers' excessive optimism. In other words, consumers may harbour overly optimistic expectations about the likelihood of preparing elaborate dishes, and when these anticipated opportunities do not materialise, they are left with products they have not used. Over time, these items are gradually pushed to the back of the cupboard and forgotten (Wansik et al., 2000).

It seems that it is not only the product type that plays a paramount role at this stage. Another aspect could be the financial status of a household. Consumers that might be expected not to buy food in excess, and thus minimize food waste, are low-income individuals (Thyberg & Tonjes, 2016), given the scarcity of resources typically associated with their economic situation (Connell et al., 2017; Daniel, 2016). It would be expected that middle-income households, which have more financial means, would waste more food than their low-income counterparts. However, studies have shown that some lower-income consumers actually waste more food than their middle-class counterparts, leading to the emergence of what is referred to as the "food waste paradox" (Porpino, Parente et al., 2015). The paradox raises the question of why individuals who can afford food least sometimes exhibit wasteful behaviour.

One potential explanation for the food waste paradox is rooted more in psychology than economics. Recent studies with meal preparers in their homes have revealed that there are strong negative and aversive emotions associated with the sight of an empty plate when one is hungry. Even years later, these preparers may consciously or unconsciously over-buy food to ensure that their families do not experience the anxiety of an empty plate (Porpino, Wansink et al., 2016).

What is worth noting is that the food waste paradox is also visible at a more macro level that is the state level. Data shows (UNEP Food Waste Index Report, 2021) that food waste among households is much higher in lower middle-income countries compared to upper middle-income countries or even high-income countries (Table 11.1).

Table 11.1. Average food waste (kg/capita/year) by World Bank income classification

Income group	Average food waste by household (kg/capita/year)
High-income countries	79
Upper middle-income countries	76
Lower middle-income countries	91

Source: (UNEP Food Waste Index Report, 2021).

However, the food waste paradox is not supported across all studies. In one study, households which noted that price was important did not waste as much food as those which noted that price was less important. The reason for this could be due to better planning abilities or cost awareness in general (Wiliams et al., 2012).

Therefore, in general, it can be concluded that the financial status of a household does not clearly determine the level of food waste. Interesting light is shed on this issue by studies (wrap, 2022a) that have investigated the impact of rising food costs (induced by inflation) on level of food waste. The majority of households clearly indicate that they are most affected by the rising cost of buying food. For this reason, they try to reduce their food expenditure mainly by buying items on sale, shopping somewhere cheaper, purchasing value brands or buying in bulk. Furthermore, most households find ways to save food and to be more resourceful (e.g., through a shopping list). However, despite all these measures, half of the households indicate that they throw away at least as much food as they did the year before (2022 vs 2021) (wrap, 2022a).

11.3. Stage II: Food is prepared but not served

The next stage of food waste pertains to food that is prepared but not served, which includes instances of over-preparation and insufficient consumption. There are several reasons why food is prepared but not eaten. This encompasses, e.g., leftovers that are stored until they become inedible, as well as instances where there are insufficient portions remaining for another meal or when the refrigerator is already at capacity. It could also include instances where food is burnt or dropped, when newly tried recipes do not meet taste expectations, or when plans change and family members eat away from home. Additionally, food that no longer meets freshness or temperature preferences loses its appeal and is left on the table until eventually being discarded (Neff et al., 2015; Qi & Roe, 2016).

However, the main driver of not serving previously cooked food is over-preparation. That means that more food is prepared than a given family is able to consume. A very interesting explanation of this issue states that food waste resulting from over-preparation may be influenced by the principles of the Prospect Theory, which posits that individuals are more inclined to avoid losses than to pursue gains (Tversky & Kahneman, 1992). According to this, those who prepare food are mostly motivated by the desire to prevent disappointment among their family members and/or guests. As a result, they may exhibit a bias towards over-preparing food as a means of avoiding the loss associated with inadequate portions or the embarrassment of insufficient provisions. Rather than conserving food and risking the dissatisfaction of hungry individuals, they prioritise averting the "loss" of disappointing others over the potential gain of reducing food waste. This is somehow related to the concept of a "good provider" which states that the willingness to offer nutritious and plentiful meals to family or guests is a major barrier to reducing food waste. The ability to provide healthy and abundant meals to those in the social circle can be seen as a symbol of the ability to protect and promote their well-being (Graham-Rowe et al., 2014).

This tendency seems to be particularly prevalent especially among those who, at some point of their lives, have experienced problems with food availability. For instance, food preparers in food-insecure households tend to over-prepare meals in order to shield their families from the anxiety of witnessing empty serving bowls, which may evoke memories of past occasions when they went hungry (Porpino, Wansink et al., 2016). This could apply in most cases to low-income families. However, it could also be related to people that have experienced food shortages due to being citizens of countries with inefficient economies. This is true in Central Europe where the communist economy forced people to struggle for food. The memory of past experiences influences especially older generations to over-prepare food.

Another issue at this stage is a general lack of utilisation of leftovers. Although surplus food could be saved and reheated for future meals, it is often overlooked. This oversight is attributed to factors such as laziness, safety concerns or a general sense of disgust (Meah & Watson, 2013). This leads to a very important question: Why are leftovers saved if they often go uneaten? One perspective is that they are saved due to the concept of "maturation time," which allows individuals to postpone the uncomfortable or wasteful feelings associated with immediate disposal of food after a meal (Waitt & Phillips, 2016).

11.4. Stage III: Food is served but not consumed

With approximately 1,000 meals per year, we should have a reasonable sense of our hunger and the amount of food required to satisfy ourselves. Additionally, adults generally have knowledge of food preferences, especially when it comes to familiar dishes. Under such circumstances, it would be peculiar if mature household members consistently overserved themselves to the point of significant waste. While it may be difficult to finish overly large portions at restaurants or other places away from home, when it comes to familiar self-served food, most of what is put on plates should be consumed.

Multiple studies indicate that plate waste amounts to less than 10% (Wansink & Johnson, 2015), providing converging evidence across different methodologies that plate waste among adults is lower than commonly assumed.

However, unlike adults, children are not well calibrated when it comes to determining the appropriate amount of food needed to satisfy their hunger. They are still in the process of experimenting and discovering their food preferences, as well as developing their taste preferences and tolerance for different flavours. While adults may know that they enjoy certain foods but dislike others, such as lamb but not eggplant or cilantro, children need to acquire this knowledge through experience. Therefore, a child who consumes only half of what they serve themselves is not wasteful but rather behaves in a manner that is considered normal for their developmental stage.

11.5. Level and structure of household food waste

Starting from the very global level, one can say that average food waste calculated per capita—ranging in most cases from 70 to 80 kg/capita/year—does not differ substantially across continents. The only exception is Africa, which, being the poorest region, wastes the most food per capita (108 kg/capita/year) (see Figure 11.1). However, drawing conclusions from these figures, we should take into account the fact that, given the scarcity of reliable data (especially in poorer regions of the world), these are only approximations.

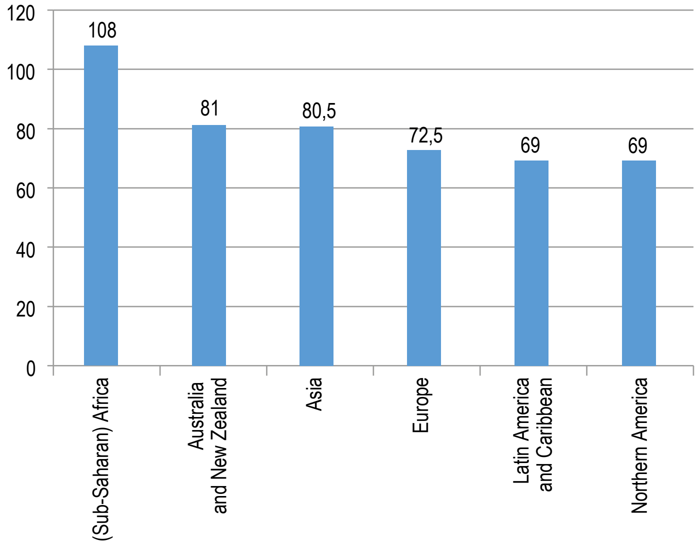

Figure 11.1. Average food waste of household (kg/capita/year) by continent
Source: based on (UNEP Food Waste Index Report, 2021).

As far as the European Union is concerned, it shall be highlighted that this is the most well-documented region among other continents regarding food waste. That results in the highest level of confidence when it comes the data. In the EU, the differences in food waste among households across different member states appear to be more significant (Table 11.2). There is a fourfold difference between the country that wastes the most food (Greece: 142 kg/capita/year) and the one that wastes the least (Slovenia: 34 kg/capita/year). It is quite difficult to enumerate the reasons for a certain level of food waste among the EU countries. For instance, differences in the level of food wastage cannot be attributed to the wealth of a country. Indeed, the highest levels of food waste can be attributed to both the middle-income countries (Greece, Hungary) and the richest countries (Luxembourg, France). On the other hand, it can be pointed out that the countries where households waste food the least are the rich countries, with the exception of Slovenia and Poland.

Table 11.2. Household food waste estimates for EU countries

EU Country	Household food waste estimate (kg/capita/year)	Household food waste estimate (tons/year)
Greece	142	1 483 996
Malta	129	56 812
Hungary	94	908 669
Luxembourg	90	55 126
France	85	5 522 358
Croatia	84	348 091
Portugal	84	861 838
Denmark	81	469 449
Sweden	81	812 948
Estonia	78	102 743
Spain	77	3 613 954
Latvia	76	145 273
Lithuania	76	210 255
Germany	75	6 263 775
EU	**75**	
Czech Republic	70	746 894
Romania	70	1 353 077
Slovakia	70	381 301
Bulgaria	68	478 667
Italy	67	4 059 806
Finland	65	361 937
Poland	56	2 119 455
Ireland	55	267 073
Belgium	50	576 036
Netherlands	50	854 855
Austria	39	349 249
Slovenia	34	71 107
Cyprus	no estimates	

Source: based on (Food Waste Index Report, 2021).

Furthermore, more cultural explanations do not provide any insightful point of view. Countries that appear to be more culturally similar have different levels of food waste. This is the case, e.g., in the Nordic countries. In Denmark and Sweden, the level of food waste at 81 kg/capita/year in both countries is higher than the EU average, while Finland's is 65 kg/capita/year, which is below the average. The same is true for Southern European countries (e.g., Greece: 142 kg/capita/year vs Italy: 67 kg/capita/year) and Central European countries (e.g., Hungary: 94 kg/capita/year vs Slovakia: 70 kg/capita/year and Poland: 56 kg/capita/year).

When it comes to defining the categories of wasted food, the issue seems to be slightly complicated. This is due to the fact that there is no widely accepted common formula for analysing the structure of wasted food by households. For example, there is no basket of goods whose wastage would be analysed. Hence, available data from different sources can only be compared with some approximation. Despite such limitations, however, it is possible to identify the main categories of food products that are most often wasted. Shown in Figure 11.2 and Figure 11.3, the structure of wasted food comes from two countries—the USA and Sweden. Despite the fact that these countries differ significantly in terms of, e.g., culture or level of taxation, the categories of food most often wasted seem to be very similar and include Fruits and Vegetables as well as Prepared Foods and Leftovers.

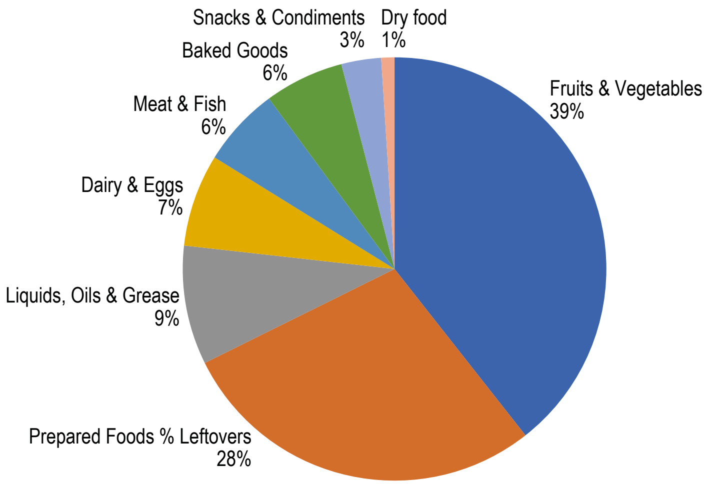

Figure 11.2. Edible food waste by category (%) (United States)
Source: (Hoover, 2017).

Interestingly, the situation in Poland seems somewhat different despite the fact that it does not generally differ from the data for the USA and Sweden. In fact, what distinguishes Poland is the fact that the most frequently wasted food by Polish

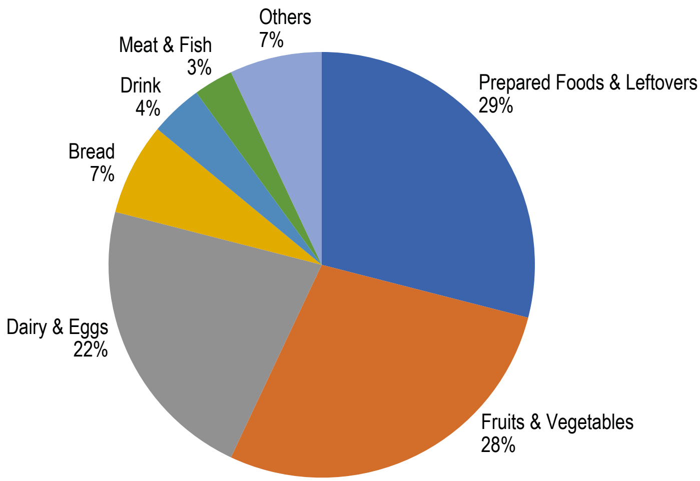

Figure 11.3. Edible food waste by category (%) (Sweden)
Source: (Hoover, 2017).

households is bread, fruits and vegetables, meats and dairy products. In Polish households, unconsumed meal components are also wasted, mainly cooked potatoes, rice and pasta or vegetables (Tomaszewska et al., 2020). However, the discarding of bread is not only characteristic of Poland. A study conducted among Norwegian households (Hanssen et al., 2016) also indicates that bread is among the most frequently wasted food products. Nowadays bread has to meet high freshness requirements, and stale bread is most often thrown away by consumers (Schneider & Lebersorger, 2012). A survey of 1,000 Austrians aged 15 years and over showed that 78% of respondents rated freshness as the most important attribute of bread (Starmayr, 2008).

11.6. Ways of preventing food waste

The issue of reducing food waste may be addressed from several perspectives. These include the perspectives of the economy, public policy, and businesses at different stages of the value chain and, of course, households.

As far as measures aimed directly at households are concerned, these take the form of recommendations relating mainly to how to handle food in order to minimise food losses within the household. It is also about households becoming more responsible and more conscious consumers of food. According to Parizeau et al. (2015) and Secondi et al. (2015), careful planning of grocery shopping is an effective tool to prevent food waste. Quested et al. (2013) indicated that there is a strong positive correlation between creating a shopping list and other behaviours, such as planning meals in advance and checking food stocks before shopping.

For household members, recommendations take the form of easy-to-follow steps such as: (Flanagan et al., 2019):

- Buy only what you expect to eat: check the refrigerator and cupboards before shopping, use a shopping list and plan meals in advance.
- Know the difference between "use by" (which is about food safety) and "best before" (which is about quality, and it is still safe to eat food after this date).
- Freeze or preserve food before it spoils and find out how to best store different foods so that they stay fresh and safe longer.
- Find creative ways to use leftover ingredients and products past their peak quality (e.g., in soups, sauces, smoothies), as well as ways to cook parts you do not normally eat (e.g., stems, cores).
- Organise the kitchen and refrigerator so that items do not get lost and spoiled.

These recommendations can also be grouped according to the process of purchasing, storing and preparing food.

11.6.1. Purchasing process

Suggestions at this stage claim that engaging in strategic planning, food preparation and effective food storage practices can substantially reduce food waste within households. The act of devising a weekly meal plan that aligns with culinary preferences can yield financial and temporal benefits. By purchasing only the necessary ingredients, one can increase the likelihood of maintaining their freshness and utilising them fully.

Streamlining one's meal choices requires households to maintain an ongoing record of favoured dishes and their corresponding ingredients. This enables easy selection, efficient shopping and seamless meal preparation based on anticipated consumption patterns. Before venturing out to buy groceries, it is prudent to inspect the refrigerator, freezer and pantry to avoid acquiring items that are already available.

To optimise resource allocation, households are advised to plan meals for the week ahead of the shopping expedition and purchase solely the required provisions. Factors such as the frequency of dining out, consumption of pre-cooked frozen meals and the intention to incorporate leftovers into subsequent meals should also be taken into consideration.

While purchasing items in large quantities, e.g. by taking advantage of buy-one-get-one-free deals, can offer potential savings, it is essential to ensure that all acquired food is utilised before it spoils. Opting to purchase food from bulk bins presents a cost-effective and waste-reducing alternative, as it allows to procure the precise amount needed rather than predetermined portions. Another crucial aspect is proper storage of bulk purchases in appropriately sealed and labelled containers.

Embracing the consumption of imperfect produce or upcycled products can also foster sustainability. Imperfect produce, despite physical blemishes, maintains its safety and nutritional value, and is often available at discounted prices. Upcycled products utilise ingredients that might have otherwise been discarded, contributing to waste reduction efforts.

11.6.2. Storing process

This stage focuses on the best possible storage methods, which often are very technical. For instance, households should keep in mind that fruits like bananas, apples, pears, stone fruit and avocados emit ethylene gas during ripening, which can accelerate the ripening process of nearby produce and potentially lead to spoilage. Therefore, it is advisable to store such items separately. What is more, certain vegetables prone to wilting, such as leafy greens, carrots, cucumbers and broccoli, fare best in the high humidity drawer of the refrigerator.

To optimise refrigeration practices, it is recommended to avoid storing perishable items, such as milk or eggs, in the refrigerator door, as it is the warmest part of the fridge.

11.6.3. Preparing food process

The main assumption at this stage is that ingredients past their prime, as well as leftover odds and ends, can still serve a purpose in cooking. Repurposing these ingredients in soups, casseroles, stir-fries, frittatas, sauces, baked goods, pancakes or smoothies not only prevents their wastage but may also result in the discovery of new favourite culinary creations. When feasible and safe, utilising edible parts of food that are typically discarded can contribute to waste reduction.

Furthermore, it is also of great importance to understand the distinctions among labelling terms such as “sell by”, “use by”, “best by”, and expiration dates, which is crucial in making informed decisions about food consumption and disposal.

Striving to cook and serve appropriate portions based on the number of individuals being fed helps to avoid excessive food waste.

It is crucial to refrain from leaving perishable food items at room temperature for more than two hours to mitigate the risk of bacterial growth and spoilage. Leftovers should be promptly refrigerated or frozen in small, transparent containers that are labelled with the date and contents to facilitate their subsequent utilisation.

Conclusions

As stated above, household food waste behaviour is influenced by various factors and interdependencies. Hence, solving this problem is not an easy or short-term process. Actions to change household attitudes towards food in general and towards food waste in particular can play a major role here. Treating food as a valuable product should lead households to become more resourceful—that is, to buy only the amount of food they can consume, thereby minimising food waste. It is open to question whether changes in attitudes towards food should be achieved through suggestions, incentives, awareness-raising (the proverbial carrot) or coercive measures, such as increasing the level of taxation as food waste increases (the proverbial stick).

Development of a consistent widely acceptable methodology for calculating the level of food waste in households remains a separate issue. This should be done so that the data collected are both reliable and comparable across countries.

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12. SURPLUS FOOD REDISTRIBUTION SYSTEMS AS A FOOD WASTE PREVENTION TOOL

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Abstract

The main objective of this chapter is to present solutions designed in order to redistribute surplus food as a food waste prevention tool. Food surpluses are generated both in supply chains and in households. This chapter presents the surplus food redistribution system structure in terms of entities included into it. Three main types of SFRS institutions will be presented: food banks operating both as front-line and warehouse entities, social supermarkets and food sharing systems, which work as initiatives based on some premises (physical places) where food may be left and taken from, as well as initiatives operating thanks to Internet platforms. Three categories of these platforms are characterised in this chapter: the "sharing for money" model, which is primarily a B2C for-profit model to reduce waste and, at the same time, generate revenue, the "sharing for charity" model in which food is collected and given to non-profit organisations, and the "sharing for the community" model which is a B2C or C2C model where food is shared amongst consumers.

Keywords: surplus food redistribution system, food bank, social supermarkets, food sharing initiatives, food sharing platforms.

JEL code: Q57.

Introduction

The contemporary model of food production and distribution is oriented on a mass-scale operations and products commodification. It results in the growing access to a wide variety of food products but, on the other hand, it contributes to the creation of a huge amount of unsaleable products. Keeping in mind the cost of food production (including the environmental cost), the amount of food wasted every year and the level of food insecurity still existing all over the world (Berti et al.,

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2021), it is absolutely necessary to develop solutions in order to use food already produced and prevent it from being wasted. Where does wasted food come from? The patterns of food waste seem to vary, based on numerous criteria, including income categorisation; lower-income countries primarily experience food waste during the production and processing stages of the food supply chain, whereas middle- and high-income countries tend to waste food more significantly during the final stage of household consumption (Amirudin & Gim, 2019). It means that food leftovers are generated practically in every country, on every level of food distribution channels, and that they all may (and should) be included into food redistribution systems, which play a twofold role: reducing food insecurity and preventing surplus food waste. There are a variety of reasons, both on the side of producers and consumers, for which food is still good for consumption but unsaleable, and may be easily turned into waste instead of being recovered. These reasons are presented in Table 12.1.

Table 12.1. Main barriers to food waste recovery

Supply side	Demand side
• stigma associated with food waste as a symbol of inefficiency • underestimation of the quantity of food waste/perception that it is not a significant issue • insufficient awareness of social and environmental impacts of food waste • regard for waste disposal as an acceptable solution • perception that food waste is inevitable and socially acceptable • belief that food waste is not the responsibility of suppliers on a personal level • lack of coordination with demand-side actors in the food supply chain • complexity in managing the recovery of perishable goods within a limited timeframe • absence of clearly defined processes and activities for food waste recovery within the food industry, seen as time-consuming, labour-intensive and costly • undefined and unapproved food waste recovery procedures at the corporate level in retail stores • lack of a system to measure and track food waste • retailers' practice of discarding products based on "sell by" dates and appearance standards • insufficient information for consumers regarding the meaning of "best-before" labels • reluctance to sell products resulting from processing errors and packaging-related issues • prioritisation of financial considerations over environmental concerns in relation to food waste disposal/recovery • limited quantities of edible waste, making recovery challenging in terms of logistics • financial and reputational risks for food businesses due to health and safety concerns associated with food donations • misconception of liabilities arising from food waste donations/transfers • lengthy donation processes and additional costs, efforts and logistical challenges • higher expenses associated with food donation compared to disposal	• consumers' reluctance to purchase imperfect/suboptimal products and items nearing the "best before" date • consumer misconceptions regarding "best before" labels • lack of coordination with suppliers within the food supply chain • retailers' practices of rejecting products based on "sell by" dates and appearance criteria • processing errors and packaging issues not deemed acceptable by potential recipients • limited financial and time resources of charitable organisations for food collection • mismatch between potential food donations and the specific needs of charitable organisations • limited resources and time for charitable organisations to handle administrative procedures associated with food donations • challenges in managing the recovery of perishable goods within a limited timeframe

Source: (Ciulli et al., 2020; Hingston & Noseworthy, 2020; Zielińska et al., 2020).

This chapter focuses on preventing food from becoming waste by delivering it to potential consumers directly or indirectly through surplus food redistribution systems. It is organised as follows: first, a surplus food redistribution system (SFRS) will be defined and its general structure will be presented; then, four types of key institutions of the SFRS will be described: food banks, social supermarkets, food sharing initiatives and food sharing platforms applying three different models: "sharing for money", "sharing for charity" and "sharing for community".

12.1. Structure of surplus food redistributive system

Food redistributive systems emerged due to a huge amount of leftovers occurring on every level of the distribution system. Their main objective is to collect food which is unsaleable but still good for consumption. Collected food may be given for free or sold (as it is or processed), and in this way both food waste and food insecurity can be reduced (Vittuari et al., 2017).

The distribution system for surplus food consists of providers (farmers, food producers and importers, wholesalers, retailers, catering companies, individuals), redistribution entities (redistributing food products and processing food) and end users (consumers). The general structure of a food redistribution system by the type of entities involved in the process is presented in Figure 12.1.

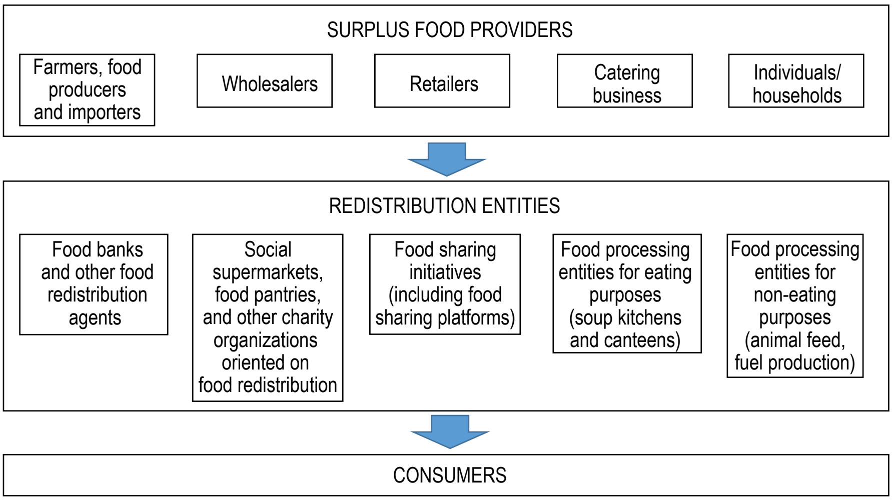

Figure 12.1. General structure of food redistribution system

Source: own elaboration.

There are a variety of redistributive entities which can be distinguished with several criteria (Michelini et al., 2018), such as:

a) organisation profile: profit or non-profit, pure player, brick and mortar, click and mortar, types of technologies: website, app, website and app, geolocation,
b) delivery models: Business-to-Consumer (B2C); Business-to-Business (B2B); Peer-to-Peer (P2P); Consumer-to Consumer (C2C), Consumer-to-Business (C2B),
c) type of donor: farmers, producers, distributors, consumers,
d) type of beneficiary: consumers, non-profit organisations,
e) type of transaction: donation or sale,
f) social impact: waste reduction, poverty reduction,
g) type of client they are oriented on: B2B (food banks), B2C (social supermarkets, food pantries), C2C (food sharing initiatives),
h) type of activity: food resell, donate, process.

The entities presented in Figure 12.1 may interplay; for example, food banks supply soup kitchens, food pantries or other charity organisations which give food to people in need. In the following part of this chapter the most important entities will be presented, including their origin, mode/s of activity and future perspectives.

12.2. Food banks

Food banks are "humanitarian aid organisations that collect, organise and deliver food to nonprofit member agencies and to individuals to help alleviate the society's hunger problem" (Ataseven et al., 2018). Their main objective is to reduce food insecurity of people in need. Food banks are usually charitable organisations that operate as nonprofit entities, aiming to provide food assistance to individuals who face difficulties in affording an adequate supply to prevent hunger. As was mentioned above, food banks typically work in conjunction with intermediaries such as food pantries and soup kitchens. The first food bank in the world—St. Mary's Food Bank—was established in the United States in 1967. Since then, a significant number of food banks has been established worldwide. In Europe, the first one was organised in 1984 in France and their numbers saw a rapid increase following the global rise in food prices that commenced in late 2006. The growth of food banks accelerated further during the financial crisis of 2007–2008, which exacerbated economic challenges for individuals with low incomes (Global Food Banking Network, 2023).

A significant differentiation among food banks lies in their operational model, primarily categorised as either the "retailer" model or the "warehouse" model. Under the first one, food banks directly distribute food to individuals in need. In contrast, the warehouse model involves supplying food to intermediaries such as food pantries, soup kitchens and other front-line organisations. In some countries (e.g., the United States and Australia), the standard approach for food banks is to function as warehouses rather than directly supply the end-users, although there are exceptions (Bacon & Baker, 2017). Conversely, in other countries (like Great Britain, France, Germany and Poland), food banks typically both distribute food parcels directly to people experiencing hunger and work as warehouses delivering food to aid organisations (Rizvi et al., 2021).

Another distinction pertains to the charity model versus the labour union model. Food banks operated by charitable organisations often prioritise food recovery efforts to prevent wastage and encourage volunteerism. Conversely, those managed by labour unions may place greater emphasis on providing nourishment to the hungry through any available means, offering employment opportunities for the unemployed, and focusing on education, particularly in informing users about their civil rights.

A food bank supply chain includes three main actors: donors, food banks and agencies. The term agency is used to describe entities (usually non-for-profit entities) that receive the food and distribute it to individuals. In some cases, donations are performed directly at the food bank; however, in most cases, the food bank organises the transportation of donations—different solutions are presented in Figure 12.2.

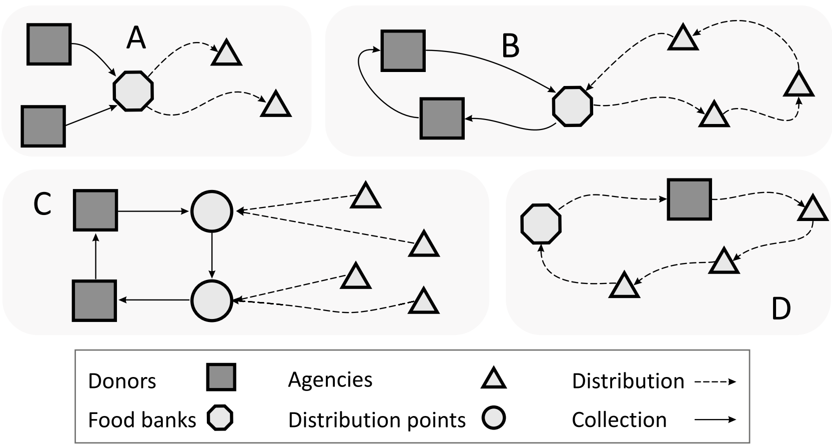

Figure 12.2. Different food bank supply chains
Source: (Rivera et al., 2023).

Food banks also receive financial donations that allow them to acquire more goods, particularly supplies that are not commonly donated. Due to typically higher demand than donations, food banks need to assess strategies to ensure fairness and equity while maximising the efficiency of their distribution operations (Rivera et al., 2023).

Redistribution of surplus food to people in need is usually presented as a win-win solution to the food paradox, despite being controversial (Caplan, 2016). It is mainly based on the fact that food banks do not always deliver proper food (in terms of quantity and quality) to their clients. Many clients of food banks consider themselves, and are considered by others, to be stigmatised. They see themselves as failures, excluded from normal society, and often claim to be ashamed that they cannot provide for their families. Consequently, it happens that donating food to a food bank does not guarantee food waste prevention. Food bank practices that are the best at meeting client needs and improving food security are those that provide culturally appropriate and suitable foods in ways that clients perceive as dignifying (Bazerghi et al., 2016). Contemporary approaches to improving services include increasing the quality of food provisions, establishing safe and welcoming spaces, as well as providing greater integration with health care and health promotion. Appropriate foods for food banks are those that are deemed safe, nutritious and able to meet special dietary requirements. Furthermore, another important issue is free choice of food; if people visiting food banks can select food items from displays, as in a grocery store, instead of receiving pre-packed hampers, it is more likely that they will utilise them all (Rizvi et al., 2021). Given the substantial dependence on donated food, educating staff and donors on the selection and distribution of suitable food items can enhance the food bank's ability to alleviate food insecurity. Overcoming operational obstacles, such as resource constraints, restricted opening hours and limited awareness of available services, is also crucial to ensure that food bank programs are inclusive and accessible to all. Meeting these conditions is vital to make food banks a tool to prevent food waste effectively.

12.3. Social supermarkets

Social supermarkets are a relatively new and specific form of social enterprises (Holweg & Lienbacher, 2011; Maric & Knezevic, 2014) and a new retail format (Lienbacher, 2012; Bogetic et al., 2018). Social supermarkets were first developed in Austria in 1990, where SOMA, a nonprofit organisation, coordinates the entire retail process in the country (from product suppliers to point-of-sale distribution). In Croatia, the first social supermarket was opened in 2009 (Michelini et al., 2018). Such supermarkets significantly developed across Europe as a response to the economic crisis (2008–2014) which caused an increase in poverty in some countries. Thus, one of their most important objectives is to address the problem of poverty and material deprivation, which is deepening in the third millennium. On the other hand, social supermarkets resolve another sustainability issue. They contribute to the reduction of food waste in traditional food supply chains. As an organisation, social supermarkets' mission is to help to redistribute food surpluses generated within traditional food supply chains to people who are at risk of poverty or in material deprivation and food insecurity (see Figure 12.2). As a new type of organisation, social supermarkets foster positive social change by fulfilling the material needs of socially disadvantaged groups and giving them an opportunity to preserve their dignity in an environment where they can choose various kinds of goods at extremely low prices (EU Fusions, 2015; Maric & Knezevic, 2014).

There are many different types of social supermarkets across Europe, but their level of existence and development is very different from country to country as it is shown in research studies done by Holweg and Lienbacher (2011), within project EU Fusions (2015), as well as by Knezevic (2018). The level of existence and development of social supermarkets is influenced by the economic situation of the country and its level of development. Therefore, there is no common, widely accepted and totally clear definition of social supermarkets, because it should be broad enough to integrate all the variations which are developed and existing in different markets. Moreover, as a relatively new phenomenon, social supermarkets are not sufficiently analysed in the literature. However, we can find a number of different definitions and determinations of the term social supermarkets. Some of the definitions are the following:

- Schnedlitz et al. (2011) defined a social supermarket as "a small, non-profit oriented retailing operation offering a limited assortment of products at symbolic prices primarily [*sic*] in self-service manner. Authorised for shopping are needy people only. The products are donated by food production and retail companies free of charge as they are edible but not marketable due to small blemishes. Achieved profit is reinvested into social projects".
- A social supermarket is "a shop selling discounted food to people on a low income" (definition given in *Collins Dictionary*).
- According to Maric and Knezevic (2014), social supermarkets constitute a new retail format that fosters positive social change by fulfilling the material needs of socially disadvantaged groups and giving them an opportunity to preserve their dignity in an environment where they can choose various kinds of goods at extremely low prices or, in some cases, free of charge.
- Some authors emphasise that social supermarkets are nonprofit organisations that base their activity on volunteerism and charity, and if they generate any profits, they use them for charitable activities (Holweg & Lienbacher, 2011).

Schneider et al. (2015) listed several benefits of social supermarkets:

- reduction of food insecurity and users' life quality improvement,
- social inclusion of the users of social supermarkets by fostering their self-confidence in communication with others and feeling of belonging,

- social supermarkets give a possibility of choice to their users and treat them as clients, and not as charity users, which strengthens the sense of dignity,
- environmental benefits due to food waste reduction,
- distribution of surplus food from a company which has the surplus trough social supermarkets to final users,
- economic benefits related with reallocation of users' scarce budgets.

In the everyday operation of social supermarkets, the management's ability to carry out donation collection and fundraising activities plays a prominent role. Figure 12.3 shows three key elements in the daily work of social self-services: (1) stakeholders, (2) frequency of donations and fundraising activities, and (3) the assortment of goods offered to customers (i.e. materially deprived citizens).

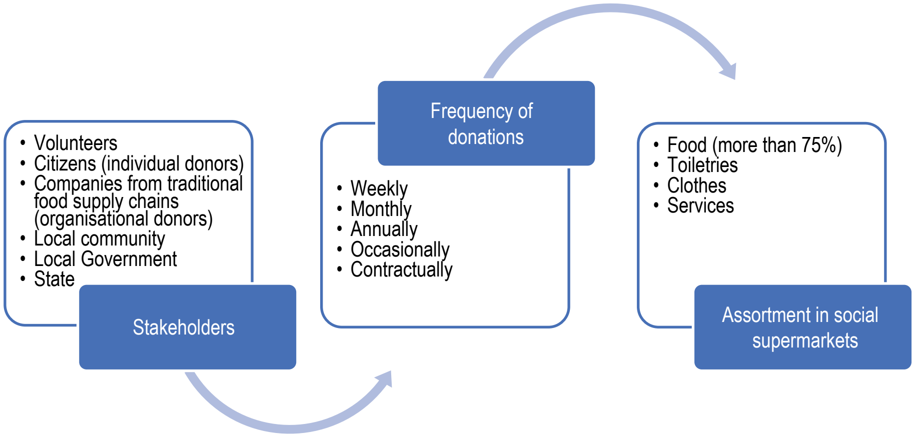

Figure 12.3. Key elements in everyday operation of social supermarkets
Source: own elaboration.

Usually, in social supermarkets, food makes up more than 75% of the assortment (see the results of studies by Holweg and Lienbacher (2011) as well as Knezevic (2018). That is why, we can claim that social supermarkets are actually a social innovation in food distribution in a way that reduces poverty and prevents hunger among the most socially vulnerable citizens. In addition, based on the conducted primary research (Holweg & Lienbacher, 2011; Knezevic, 2018), social supermarkets dominantly collect donations of food and toiletries: (a) directly from producers, (b) from fast-moving goods (and/or grocery) retailers, and (c) from individuals. The structure of donation sources varies from county to country, and the legal frameworks regarding food donations directly influence the structure of donation sources.

12.4. Food sharing initiatives

Food sharing involves collecting unwanted and overproduced food products (which would otherwise be discarded) and redistributing them to people who will consume them. The food products can be collected directly from private households (donated by individuals) as well as from small or medium-sized businesses (restaurants and stores mainly). It can be distributed either directly via distributors or through online communities. In the following subchapter, attention will be focused on the offline solutions. They can be organised either by institutions dedicated to social work (mainly) or by individuals. They require space and equipment (cupboard, refrigerator), as well as a good communication system and purposely designed rules explaining what kind of food may be shared. For example, Jadłodzielnie Warszawskie (Warsaw Foodsharing) states that one can bring products that are fit for consumption, have exceeded the date of minimum durability ("best before"), but have not exceeded the expiry date ("use by"). They should be tightly packed and placed in clean containers. Homemade products, e.g., sandwiches, cake, soup, should have a description of the dish, as well as the composition and date of preparation. Dry products can be opened but should be sealed tightly. Rotten products, raw meat, dishes with raw eggs or unpasteurised milk are unacceptable (JedzeNIEwyrzucaj, 2021). Appointed guardians, but also the users themselves, take care of order and cleanliness. In this type of initiatives, the primary concern raised frequently is the challenge posed by food risk policies. In particular, the phenomenon of community refrigerators has created a flash point for food risk enforcement. At the core of the tensions between food sharing initiatives and regulators lay a fundamental difference in their perception of risk allocation. Legislative requirements place the responsibility on an accountable individual to demonstrate adherence to the cold chain during food redistribution. On the other hand, food sharing initiatives often espouse a vision that is more rooted in a commons-based approach to risk and responsibility. The 2017 food donation guidelines issued by the European Commission, primarily motivated by a global campaign to raise awareness and take action against food waste, emphasise the requirement for donated food to be traceable and edible in line with existing food hygiene regulations. However, these guidelines do not specifically outline the roles and responsibilities of the various stakeholders involved in ensuring compliance with these guidelines. As a result, uncertainties persist regarding who should be responsible for providing and financing the new logistics infrastructure necessary to accommodate the increased volumes of redistributed surplus food, as well as who should assess the quality and suitability of surplus food for consumption (Davies et al., 2019).

12.5. Food sharing platforms

Food sharing platforms are nowadays recognised as the nexus of various issues that are seen as critical for sustainability, such as waste reduction, social inclusion and community engagement (Schanes & Stagl, 2019). Using digital technologies, such as mobile apps and websites, they create a secondary market for the distribution of food surplus, simplify the process of sharing, gifting and selling items, and spread the practice of sustainable food consumption (Bachnik & Szumniak-Samolej, 2018). Michelini et al. (2018) categorised food sharing models into three types based on the specific marketplace they operate in. Each model is distinguished by unique logistical processes that involve various actors, including providers (businesses or private individuals) and final consumers (users or non-profit organisations).

The initial category of food sharing is represented by the "sharing for money" model, which is operated by for-profit organisations. This model primarily follows a business-to-consumer (B2C) delivery approach, where distributors, retailers and restaurants can list their unsold products on a website or app. Consumers have the option to browse and purchase discounted food either online or directly from the physical store. Some scholars consider this model to be more akin to traditional offerings and classify it as "pseudo-sharing" (Belk, 2014) or "redistribution" (Lago & Sieber, 2016), as it involves monetary compensation. TooGoodToGo is a good example of this type. It was established in 2016 in Denmark as a B2C platform, and it operated in 17 countries in June 2023, mainly in Europe, but also in Canada and the United States, having over 17 million users. Their model is mainly based on a web-based app where food suppliers (stores, restaurants) may register available food which is next reserved by app-users who pay a reduced price for products and pick them up on their own (TooGoodTooGo, 2021).

The second model is known as "sharing for charity" and is managed by non-profit organisations, both in an online-only (pure player) and physical (brick and mortar) setting. The primary delivery approach for this model is business-to-business (B2B), business-to-non-profit organisation (B2NPO), and consumer-to-business (C2B), where food is collected from various donors. It is then distributed predominantly free of charge to non-profit organisations at the local and national levels. Food Rescue US is an example. It was founded in 2011 when its two founders, Jeff Schacher and Kevin Mullins, recognised that two growing challenges facing their community and the nation, i.e. food insecurity and food waste, could be solved with innovative technology, volunteers and a direct-transfer model. They founded Community Plates and created a unique model of food rescue that is simple, sustainable and scalable. The whole system works thanks to a web-based app, through which food donors register available food, social service agencies communicate their food needs and details for delivery, and volunteers sign up for a “food rescue”. Once a match is made between a food donation opportunity and a social service agency, a volunteer rescuer self-schedules to pick up the food from the donor and deliver it directly to the local social service agency serving the community. In June 2023, Food Rescue US was in 43 locations across 25 states and the District of Columbia (Food Rescue US, 2023).

The third model “sharing for the community” is operated by profit and non-profit organisations that operate as pure players. The delivery model in this case is P2P, meaning that food is collected primarily from consumers (in some cases also from business entities) and shared with other consumers at a local level. The goal of this model is to serve a community actively in reducing food waste, and it is considered as “pure or real sharing” when it involves “a resource that was previously used individually or was completely idle during certain times is [*sic*] now shared across customers” without asking for a compensation (Pisoni et al., 2022). The app called OLIO may serve as an example in this case. It was launched in 2015 by a British-American team thanks to over $50 million collected in five rounds of a fundraising campaign. It was designed as a C2C “sharing for community” platform, dedicated not only to save food leftovers but also to foster the creation of social ties. At the community level, OLIO has over 60,000 trained volunteers who are matched with a business in their neighbourhood (a retailer or a restaurant). On their allotted time and day, a volunteer visits this business and collect all the unsold or unserved food. Then, they take it home, where they may save a part for themselves (10% as a “thank you”), and next, give it to the OLIO app; within minutes their neighbours may request it and finally pick it up. On average, food is usually fully redistributed into multiple homes in less than two hours, thereby enabling the businesses to have zero food waste locations. The OLIO app is also used for non-food household items to be given away as well as for borrowing everyday things instead of buying brand new ones (Olio, 2023a). The app had approximately 7 million users around the world in June 2023, and OLIO is a carbon negative company because it diverts far more greenhouse gas emissions than it produces (Olio, 2023b).

Conclusions

The food waste hierarchy ranks surplus food donations for human consumption as the next best strategy, when food waste cannot be prevented. Presented forms of surplus food redistribution systems are generally assessed as an effective way of food waste prevention (Sundin et al., 2022). Although there has not been much research on this issue so far, it was found that it has a positive environmental impact. For instance, considering global warming, Eriksson & Spångberg (2017) found an average avoided impact of 0.6 kg CO_2 eq/kg of food donated (only fresh fruit and vegetables), Albizzati et al. (2019) reported the impact reduction ranging between 0.5 and 2 kg CO_2 eq/kg, and Damiani et al. (2021) stated that the average net environmental benefit of food donation was 1.9 kg CO_2 eq/kg. Measuring SFRS effectiveness is a very complex task as it requires including also other effects, such as the amount of energy consumed by SFRS, direct and indirect rebound effects associated with re-spending of substitution-related monetary savings, as well as the share of redistributed food eaten (Sundin et al., 2022). Reducing food insecurity is another important positive effect that cannot be ignored. However, even if SFRS are effective in preventing food waste, it remains vital to reduce surplus food at every level of food production and consumption.

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SUMMARY

Sustainably achieving global food security is one of the foremost challenges of our time. It necessitates research and the popularization of issues related to both the production and consumption of food in a sustainable manner. On one hand, the focus of research lies in the development of technologies and processes that enable the production of food with minimal losses and a reduced negative environmental impact. On the other hand, efforts are directed towards strengthening positive attitudes among food consumers, promoting environmentally friendly diets, and reducing food losses.

The primary aim of this book is to present issues related to the development of sustainable food systems, considering both production and consumption aspects. Addressing the challenge of making food production and consumption sustainable is a goal embraced by the authors of this monograph. The book is divided into two parts: the first delves into the issue of food sustainability from the production perspective, while the second explores it from the standpoint of consumption. Given the complexity of food systems, achieving their sustainable transformation requires a system thinking approach and collaboration across inter- and trans-disciplinary domains. Consequently, this monograph explores the technological, environmental, social, and economic contexts of problems associated with food production and consumption. It covers various aspects of the food value chain, spanning from harvesting and raw material production to processing, distribution, marketing, consumption, recycling, and disposal.

The book's chapters encompass literature reviews, original research, and perspectives. The objective is to disseminate the concept of food sustainability among scientists, researchers, and practitioners directly and indirectly involved in food production and consumption. We sincerely hope that this monograph will contribute to making processes related to food more sustainable, even if only to a modest extent.

Katarzyna Pawlak-Lemańska
Barbara Borusiak
Ewa Sikorska

The book covers all aspects related to sustainability in the agri-food sector, both from a technical and economic point of view following an interesting multidisciplinary approach.
The book offers a panoramic vision of the topic, involving different disciplines that treat the topic from different points of view. It can be used by students or researchers who want to approach the topic.

Prof. Giulio Mario Cappelletti, University of Foggia

Sustainable food security is a pressing global challenge, requiring research and advocacy for both production and consumption practices. On one hand, the focus of research lies in the development of technologies and processes that enable the production of food with minimal losses and a reduced negative environmental impact. On the other hand, efforts are directed towards strengthening positive attitudes among food consumers, promoting environmentally friendly diets, and reducing food losses.
This book aims to address this challenge by exploring sustainable food systems from production to consumption. Through literature reviews, original research, and perspectives, the book seeks to disseminate the concept of food sustainability to scientists, researchers, and practitioners. We hope this monograph will contribute, albeit modestly, to making food processes more sustainable.