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SUSTAINABLE FOOD SYSTEMS: FUNCTIONAL FOODS AND MANAGEMENT OF FOOD WASTE

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ABSTRACT
The increasing global population, changing consumption patterns and climate change are putting significant pressure on food systems. There is a strong focus on the development of sustainable food systems that prioritize the efficient use of resources, reduce environmental impacts, and ensure that everyone has access to healthy nutritious food. Functional foods are known for their high nutritional values and beneficial bioactive components that positively affect human health. Additionally, they have the potential to help reduce food waste. This review examines the relationship between functional foods and sustainable nutrition and the impacts of food waste in this context by referencing current academic literature. Also, detailed examination of upcycled foods that revalue food waste and attribute economic value according to circular economy principles were given. It is expected that reducing food waste will provide significant benefits for the environment, economy, and health through the inclusion of sustainable nutrition practices and functional foods.
Keywords: Upcycled foods, functional foods, food waste, sustainable nutrition, sustainable food systems

SÜRDÜRÜLEBİLİR GIDA SİSTEMLERİ: FONKSİYONEL GIDALAR VE ATIK YÖNETİMİ

ÖZ
Artan küresel nüfus, değişen tüketim alışkanlıkları ve iklim değişikliği, gıda sistemleri üzerinde önemli bir baskı oluşturuyor. Kaynakların verimli kullanımına öncelik veren, çevresel etkileri azaltan ve herkesin sağlıklı besleyici gıdaya erişimini sağlayan sürdürülebilir gıda sistemlerinin geliştirilmesine güçlü bir şekilde odaklanılmaktadır. Fonksiyonel gıdalar, yüksek besin değerleri ve insan sağlığını olumlu yönde etkileyen faydalı biyoaktif bileşenleri ile bilinmektedir. Ek olarak, gıda israfını azaltmaya yardımcı olma potansiyeline sahiptirler. Bu derleme, fonksiyonel gıdalar ile sürdürülebilir beslenme arasındaki ilişkiyi ve bu bağlamda gıda israfının etkilerini güncel akademik literatüre atıfta bulunarak incelemektedir. Ayrıca, döngüsel ekonomi ilkelerine göre gıda israfını yeniden değerlendiren ve ekonomik değer atfeden ileri dönüştürülmüş gıdaların detaylı incelemesine yer verildi. Gıda israfının azaltılmasının, sürdürülebilir beslenme uygulamaları ve fonksiyonel gıdaların dahil edilmesi yoluyla çevre, ekonomi ve sağlık için önemli faydalar sağlaması beklenmektedir.
Anahtar kelimeler: Fonksiyonel gıdalar, ileri dönüştürülmüş gıdalar, sürdürülebilir beslenme, sürdürülebilir gıda sistemleri, yemek israfı

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INTRODUCTION

Today's food systems are vital to environmental sustainability, public health, and economic prosperity. The growing global population, shifting consumer preferences and climate change among other reasons are intensifying food system difficulties. Integrating functional foods into sustainable food system practices promotes resource efficiency, reduces environmental impact, and assures enough food access for all (FAO, 2017; Essa et.al., 2023).

The bioactive components of functional foods have positive effects on human health while also aiming to support environmental balance within the concept of sustainable nutrition (Maqsood et.al., 2020; Santini, 2022; Durazzo et.al., 2022). Sustainable nutrition is the shaping of dietary habits to protect human health and ensure environmental balance (Ruben et.al., 2021; Fanzo et.al., 2022). The enhancement of human well-being and the establishment of ecological balance also encompass economically and socially efficient and fair food production processes (Mustafa et.al., 2021; Sirdey et.al., 2023). However, food waste negatively affects the efficiency of these systems making it difficult to achieve sustainability goals (FAO, 2019).

The major goal of this review is to discuss how functional foods might be integrated into sustainable nutrition systems and to estimate the impact of food waste in this setting, drawing on existing scientific literature. Also, the health benefits of functional foods, how they contribute to environmental sustainability and what they mean economically were examined.

FUNCTIONAL FOODS, BIOACTIVE COMPONENTS AND THEIR EFFECTS ON HEALTH

From a physiological and metabolic standpoint, the active ingredients in functional foods can be viewed as powerful agents against a range of illnesses in the body (Otles and Gokgunnec, 2024). Flavonoids, fiber, essential fatty acids, probiotics, prebiotics and postbiotics are the primary elements that have a good impact on human health. They contribute to boosting antioxidant ability, postponing structural alterations in antimicrobial cells and bolstering immunity as immunomodulators, among other health advantages (Granato et. al., 2020; Jędrusek-Golińska et.al., 2020; Zaky et.al., 2022).

Liu and colleagues have shown that plant sterols can lower lipid levels through synergistic mechanisms that reduce the risk of cardiovascular disease (Liu et. al., 2024). The efficacy of probiotics to support the maintenance of balanced gut flora is well-known (Indira et. al., 2019). Omega-3 fatty acids can lower the risk of coronary heart disease, according to randomized controlled trials (Salar and Kuruüzüm-Uz, 2021). Additionally, through synergistic effects, antioxidants can improve therapy outcomes for cancer patients (Sever et. al., 2023).

In a review examining the functional food market, the health benefits of these foods are highlighted with specific examples. It points out that government-approved foods often hold bioactive ingredients such as probiotics that support digestive health, antihypertensive peptides that help regulate blood pressure, omega-3 fatty acids that lower triglyceride levels and fiber that helps control blood sugar (Iwatani and Yamamoto, 2019). Recent regulatory modifications have expanded the scope of health claims to include fatigue, eye health, memory enhancement, stress management, sleep quality, joint health, and circulation.

For example, according to studies, various components contained in functional foods can help health. Probiotics and prebiotics, contribute to digestive health by regulating gut flora (Pop et.al., 2019; Baroni et.al., 2024; Tinrat and Chomnawang, 2024). It is known that omega-3 fatty acids support cardiovascular health and have anti-inflammatory properties (Kelling et.al., 2024; Tseng et.al., 2024). Additionally, plant-based bioactive compounds can reduce the risk of cancer development and strengthen the immune system due to their antioxidant effects (Mir et.al., 2024). Among the micronutrients involved in physiological processes, it is emphasized that vitamins and minerals (Mu et.al., 2024) play a role

as anti-inflammatory agents in the body, which may counteract cell apoptosis (Cheng et.al., 2024; Yang et.al., 2024). Vitamin D is necessary to keep bone health (Sundar et.al., 2023; Nakamura, 2024); vitamin B12 is needed for the effective functioning of the nervous system (Santos et.al., 2024). Minerals such as calcium, magnesium, and iron are also important for regulating various body functions (Yu et.al., 2023; Suliburska et.al., 2024). Foods having dietary fiber make significant contributions to digestive health, serum cholesterol management and the development of gut microbiota (Ademosun et.al., 2024; Koc et.al., 2024; Cisternas et.al., 2024; Zheng et.al., 2024; Lee et.al., 2024). Omega-3 fatty acids contribute to the regulation of blood pressure by supporting vascular integrity, lowering low-density cholesterol, and controlling triglyceride levels (Asgary et.al., 2018; Shahidi and Ambigaipalan, 2018). Probiotics and prebiotics can aid manage chronic conditions such as type 2 diabetes, irritable bowel syndrome and inflammatory bowel diseases (Yadav et.al., 2022). Antioxidants and phytochemicals are critical for avoiding oxidative stress and chronic inflammation by lowering free radical-induced cellular damage (Kim and Kim, 2018). While vitamin D is known to reduce the incidence of osteoporosis (LeBoff et.al., 2022) calcium, phosphorus and magnesium are needed for bone health (Rondanelli et.al., 2021; Couce and Saenz de Pipaon, 2021). Vitamin C, zinc and probiotics all help to improve the immune system (Siripornpanich et.al., 2022; Djordjevic et. al., 2022).

These health advantages emphasize the value of functional foods and bioactive components in our diet. However, before consuming these meals, visit a healthcare practitioner to ensure that specific needs and health circumstances are met.

SUSTAINABLE NUTRITION AND GLOBAL APPLICATIONS

Sustainable nutrition is defined as a form of nutrition that adopts the principle of low environmental impact while ensuring food and nutrition security for present and future generations and promoting healthy lifestyles (Auestad and Fulgoni, 2015). The main goals of sustainable nutrition are to supporting optimal growth and development of individuals, improve physical, mental, and social well-being throughout life, prevent various forms of malnutrition, and reduce the risk of diet-related non-communicable diseases. In addition to reducing the risk of non-communicable diseases, it also includes aspects such as providing a fair source of food in terms of quality and price for people living in both rural and urban areas and protecting biodiversity and planetary health (Burlingame and Dernini, 2012; FAO and WHO, 2019). Within this framework, factors such as land use, waste management and greenhouse gas emissions are also included in the concept of sustainable nutrition (Gülsöz and Altan 2021).

Foods have significant impacts on the environment through various means such as greenhouse gas emissions, land use, and water resource use. Especially the trend towards Western-style diets, which are heavily based on high-calorie and animal products, significantly amplifies the environmental impacts of food systems. Due to the continuous increase in the global population and the continuation of current dietary habits, global food consumption is projected to increase by approximately 100% between 2005 and 2050 (Biermann and Rau 2020). Considering these risks, sustainable nutrition methods offer significant opportunities to protect both human health and the planet's ecological balance. However, adopting these sustainable habits can be challenging. Factors such as the insufficient understanding of the concept of sustainable nutrition by consumers, the lack of awareness about the environmental impacts of consumed foods, and the lack of knowledge that carbon and water footprints can be reduced even with simple changes in diets, increase this challenge (Rose et.al., 2022).

A study conducted in the UK (Whittall et.al., 2024) showed that the level of knowledge and awareness about sustainable diets had an impact on the tendency and initiatives to make sustainable changes. According to the results of the study, although the participants were confused about how to make their eating habits

more sustainable, they said that they were willing to make changes in their diets. However, in terms of dietary content, sustainable diets can be confused with healthy diets (Al Masri and König, 2025). In another study conducted in Belgium (Cooreman-Algoed, 2024), various dietary models were evaluated, and it was found that all dietary models showed significant improvements in the Alternative Healthy Eating Index score but caused an increase in water consumption. However, it was also stated that it is possible to create healthy dietary models without increasing the environmental footprint (Mirzaie-Nodoushan, 2020). With this aim, a study was conducted in China to create a dietary model that improves holistic health while also significantly reducing environmental footprints. The findings of the study showed that a diet model designed optimally for Chinese individuals could reduce the environmental footprint by 1.8 times. These results emphasize how important effective dietary models and policies that lead to sustainable nutritional options are in protecting the health and environment of individuals living in rural and urban areas (Dou and Liu, 2024). The existence of proper nutrition policies for healthy and environmentally friendly diets is significant, especially due to different food preferences in rural and urban areas (Wang et. al., 2024).

The Mediterranean Diet is one of the diets that is suitable for both health and sustainability (Metin et.al., 2024; Lorca-Camara et. al. 2024; Álvarez-Álvarez et. al., 2024). In a study conducted by Alvarez et al., it was found that after a one-year Mediterranean Diet intervention was applied to the participants, the environmental impact decreased significantly across all parameters analyzed. In addition, it was found that meat products have the greatest environmental impact among different food groups (Álvarez-Álvarez et. al., 2024).

FOOD WASTE AND ENVIRONMENTAL IMPACTS

Food waste is the situation in which edible food is abandoned or spoils owing to over-preparation, inappropriate storage, or inefficient processing (Kanwal et. al., 2024). As of 2022, it was estimated that around 1.05 billion tons of food were wasted worldwide at the household, food service, and retail levels. Between 2010 and 2022, Asia-Pacific had the highest average annual food waste of 70.28 kg per capita, while Europe had the lowest at 34.45 kg/person/year. In Europe, non-EU member countries had higher average food waste (56.88 kg/person/year) than EU member countries (34.33 kg/person/year) (Krah et. al., 2024).

Individuals at the consumer end of the food supply chain are held responsible for a huge part of global food waste. Despite the preventable nature of food waste, consumers account for approximately 88% of total food waste. All countries, regardless of their income level (high, middle, or low), contribute significantly to food waste (United Nations Environment Programme, 2024; Liechti et. al., 2024). Avoidable waste is defined as food that was previously edible but has since turned inedible. Unavoidable wastes include non-edible substances like eggshells. Potentially avoidable wastes include wastes that are rarely consumed, such as potato peels (Kohli et. al., 2023). Food waste results in significant economic, social, and environmental problems. The loss of physical products, waste from production inputs (agricultural chemicals, water, etc.) and the energy used to support quality and safety throughout the supply chain contributes to greenhouse gas emissions, which is a concern for the environment (Gage et. al., 2024). Consumers' wasteful behaviors towards food primarily begin in the home environment. Food waste in homes is influenced by several factors such as consumption habits, packaging, planning skills, socioeconomic factors, and levels of environmental awareness. Understanding the factors that affect food waste can help policymakers, academics, and experts develop more effective intervention strategies (Deliberador et. al., 2023).

In a study conducted in Iran, it was found that the religious consequences of food waste were the most effective factor in predicting food waste behavior. Furthermore, it was metioned that homes with a high socioeconomic class were

more likely to reduce food waste, but those with low income were more likely to waste food (Adaryani et. al., 2024). A comparable study in Poland examined the link between food waste and socio-demographic and economic factors. Data obtained from 500 households showed that there was an annual average of 62.6 kg of edible food wasted and 98.2 kg of non-edible components were wasted. While the amount of food waste was affected by factors such as the number of children, monthly income, age, and employment status of the person preparing the food, it was stated that the most frequently wasted foods were fruits and vegetables, bread, dairy products, beverages, fruit juices, and cold meats (Bilska et. al., 2024). Personal awareness also contributes significantly to food waste reduction (Deliberador et. al., 2023; Secer et. al., 2023). A cross-sectional study conducted in Turkey investigated the effects of personal awareness and social factors in reducing household food waste among consumers in Ankara, Izmir, and Adana. The results of this research show that consumer knowledge is a key source of incentive in minimizing food waste. The authors of the research claimed that economic knowledge had a higher influence on minimizing food waste than awareness of environmental issues (Secer et. al., 2023).

Various strategies are recommended to prevent food waste, such as weekly meal planning, part control, considering the difference between end dates and recommended consumption dates (van Rooijen et. al., 2024). Practices such as tracking food waste in public food areas such as restaurants and cafes, using composting methods, designing menus to minimize waste, and donating food that is still consumable can be effective in reducing food waste (Reardon et. al., 2024; Lévesque et. al., 2024). Within the scope of sustainable waste management, practices such as evaluating food as animal feed can also support food security (Aleisa and Alsaleh 2024).

FUNCTIONAL FOODS IN SUSTAINABLE FOOD SYSTEMS, WASTE MANAGEMENT AND INTEGRATION POTENTIAL

Sustainable food systems have many goals for human and environmental health. To make resource use efficient by supporting the reduction of food waste; to support sustainable agricultural practices, such as organic farming; Issues such as using packaging prepared using recyclable biodegradable materials are among the goals of sustainable food systems (Ahmad et. al., 2024). Sustainable unrefined materials (algae, vegetable protein sources and insects) are being researched for efficient resource use. Getting started from plant sources will make it easier to integrate sustainable protein sources into the food system. Functional components obtained from plant sources; It will be effective in reducing the environmental impacts that enhance traditional agriculture. It will be additive to the ecosystem service by ensuring food traceability (Yu et. al., 2024). Organic farming methods that can be developed within sustainable food systems; It is a powerful step towards improving the oil health and protecting water resources. Improving soil health helps to support soil carbon sequestration, thereby reducing greenhouse gases. Protecting water resources will also be able to prevent water shortage. In agriculture, as a method, rainwater reaping will reduce the pressure on water resources and support ecosystem sustainability (Bhattacharya et. al., 2024). The fact that the energy sources needed for agricultural, packaging, processing and distribution stages consist of renewable sources significantly reduces the environmental footprint. For example, the use of energy-efficient materials suppresses fossil fuel consumption. Facilities that produce their own energy can be proved, and the use of algae as a raw material source, both the fact that they can be grown at cost-effective prices and that they can produce biomass quickly, make algae a promising source in the sustainable food system (Dewan et. al., 2025; Gurau et. al., 2024; Esfandiari Bahraseman et. al., 2025; Pastrana-Pastrana et. al., 2025). Data collected in agricultural, processing and distribution stages; can create policies for sustainable food systems. Finding environmental

impacts and describing areas for improvement; It allows the development of sustainability strategies (Alsaffar, 2016; Lutz, 2021).

Recycling food waste within sustainable food systems contributes to both the protection of product quality and the prevention of waste. This also presents an important opportunity to increase consumer awareness and adopt circular economy principles. Upcycled foods; It create environmental, social, and economic benefits. Storage of food waste, preventing waste generation, reducing the use of existing resources and energy by opening new agricultural areas, using food wastes as compost and fertilizer; reflects the environmental benefits of upcycled foods. Reducing the cost given by businesses for waste management, marketing of upcycled products, supporting local food production; This encompasses the economic benefits of foods. Upcycled foods as a social benefit; It contributes to environmental protection and a circular economy by raising awareness of new workforce and reducing food waste (Thorsen et. al., 2024). Consumers' positive expectations towards upcycled foods, especially the increasing adoption of these foods by young and highly educated individuals, show that this approach will become increasingly widespread (Yilmaz and Kahveci 2022). We can count the benefits of upcycled foods to the circular economy: the use of food wastes, such as straw, for biogas production, the processing of fruit and vegetable pulps as a source of fiber for other foods, and the recycling of fruit wastes using composting methods. Thus, it will be possible to reduce the workload in agriculture, reduce the use of chemical solvents, and promote economic development (Ristivojević et. al., 2024).

The development of processing and packaging methods against the rapid spoilage of food ensures both to preservision of food freshness and to extention of the shelf life of food. Appropriate processing techniques, such as vacuum packaging, are seen as methods that preserve the nutritional value of food and reduce the amount of waste. Sustainable packaging techniques, using recyclable biodegradable packaging, and using uniform material to speed up recycling; provide welding design. Smart packaging can be used to improve food safety. In the evaluation of domestic wastes, composting organic products such as fruits and vegetables and garden waste is effective. It is necessary to adopt conscious and sustainable approaches at every stage, from the use of household waste in the kitchen to effective food processing and packaging practices, to the evaluation of functional and upcyclable foods (Gonçalves and Maximo 2023).

CONCLUSIONS AND FUTURE PERSPECTIVES

Within the scope of sustainable food systems, there are studies evaluating the effects of functional and recycled foods to prevent food waste and ensure waste management. These studies reveal that functional foods support human health and have the potential to reduce environmental impact in sustainable production methods. Recycled foods, on the other hand, offer a solution to food waste, which is a potential problem of sustainable systems.

Future research should focus on the health effects of functional and recycled foods, sustainable production techniques, processing methods, and consumer behavior. Technological innovations and policy implementations should improve food production processes and reduce waste generation through effective packaging solutions. Governments should address the issue with a comprehensive approach by developing supportive policies for sustainable food systems, sustainable business models of enterprises, conscious choices of consumers, technological developments of research institutions and awareness studies of non-governmental organizations.

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