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Sustainable Food Innovation

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To my lovely wife

Preface

Everybody agrees that the human diet must be sustainable, but what is sustainability? Firstly, it is producing food in a way that minimizes the use of resources (water footprint) and the emission of pollutants (carbon footprint). Plus, food must be nutritious. That means delivering enough quantity of essential nutrients that are easily accessible for our body to absorb. Also, what is a sustainable, nutritious food if it is not tasty and affordable? Therefore, sensory quality and price must be considered. Innovation comes to the rescue, offering solutions to these challenges. Growing global population and limited natural resources are a challenge for humanity. Food production is responsible for the use of resources and the emission of greenhouse gasses. Informed decisions made by consumers can reduce such impact, by choosing sustainable, nutritious, and affordable foods. When choices are not enough, scientific and technological innovations allow us to make a difference. The food industry proposes a variety of products, so it can be confusing for consumers to navigate themselves through them. In addition, academia focuses on very specific problems, as experts should do, thus only providing one piece of the puzzle. Consequently, the need for this book. It is a comprehensive discussion of traditional and innovative foods: nutritional profile, environmental impact, and consumer acceptability. It is the big picture that we need to make our own informed decisions. The approach chosen is multidisciplinary, simple, and easy to read, while providing high-quality scientific content. The book is structured in two parts.

The first part introduces the key concepts of sustainability, such as water and carbon footprint, in Chap. 1. Chapters 2–8 discuss traditional and innovative sources of nutrients. Three aspects are analyzed: nutrition (quantity and quality), environmental impact (water footprint, carbon footprint), and acceptability (sensory profile, price). Each chapter focuses on a specific nutrient, considering foods that contain it in high quantity. Chapter 2 is about carbohydrates as source of energy (starch, sugar). Chapter 3 is about carbohydrates as source of fiber (soluble, insoluble). Chapter 4 is about the highly discussed topic of protein. Chapter 5 is about fats (saturated, unsaturated, omega-3 fatty acids). Chapter 6 is about minerals (electrolytes, trace minerals). Chapter 7 is about water soluble vitamins (B1, B2, B3, B5, B6, B7, B9, B12, C). Chapter 8 is about fat soluble vitamins (A, D, E, K).

In the second part, the focus is on specific topics of interest, combining consumer study (marketing, sociology) with science and technology (nutrition, processing). Chapter 9 presents non-essential, yet useful nutrients, such as bioactives responsible for the management of type 2 diabetes. Chapter 10 presents the latest innovations on alternative proteins, such as insects, mycoprotein, and microalgae. Chapter 11 explains upcycling, offering market insights on new value-added products. Chapter 12 is about clean label, specifically the use of non-thermal technologies to increase food quality and safety. Finally, Chap. 13 looks at how the food industry affects water quality.

Sustainable Food Innovation is an easy read, high-quality book for everybody. Edited by a researcher who worked in the industry and lived in three continents, and written by researchers and alumni from numerous countries, *Sustainable Food Innovation* is a tool for all consumers who care about nutrition, the environment, and their budget. On behalf of all contributors, I hope you will enjoy this resource and make good use of it. Our goal is to help you make informed decisions when choosing food. Traditional or innovative, simple or processed, animal or plant based, you choose.

Enjoy!

Lincoln University, Christchurch, New Zealand Luca Serventi

Acknowledgments

Life is a constant growth. We face happiness and challenges. We learn and improve. The same approach goes into work. Keeping in mind that the best way to go far is enjoying the journey with family, friends, and colleagues.

Thanks to Mitchell Adair for helping create the book cover. This second book means a lot to me. I love promoting innovations and food choices that make our food supply nutritious, sustainable, and affordable. This is the result of hard work at university, but also outside of it: at dinner parties learning from others, at the supermarket checking out new products, and other adventures. This is possible thanks to the support of my lovely wife Lindy. Finally, a heartfelt thank you to a group of true friends: Thomas Corradi, Bryan Finfrock, Ben Yeap, Missy Utz-Finfrock, Michael Finfrock, Dr. Yu Zhang, Dr. Venkata Chelikani, and Dr. Federico Tomasetto.

Grazie amici!

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1 Food Sustainability

Damir Dennis Torrico, Xin Nie, and Luca Serventi

Abstract

Food is inseparably connected to humans' lives. The accelerated growth of the global population is systematically depleting all renewable natural resources on the planet. Water scarcity and pollution are becoming serious challenges for current food production systems. Changes in the global economy, climate, crop and animal production, consumer behaviours, and governmental policies have all affected food systems. In this context, sustainability is becoming a key issue for the production of foods. This chapter will define food sustainability and describe the effects of food production systems on the environment and society. Topics such as food waste, local food movements, carbon/water footprints and pollution will be discussed. Besides, the importance of coordinated efforts among governments, industries, and consumers will be highlighted to adopt sustainable food production systems.

Keywords

Sustainability · Carbon footprint · Consumer behaviour · Food security · Pollution · Public health · Water footprint

1.1 Introduction

Food sustainability is defined as the manufacturing of foods with a productivity level that is considered enough to feed the human population and, at the same time, to keep the accessibility to fertile land, freshwater, nutrients, macro and microfauna, and a suitable climate (Morawicki & González, 2018). Food is inextricably linked to humans' lives. People not only acquire sustenance straight from the wild but also learn to raise animals and produce plants as society progresses. Overall, changes in the global economy, climate, crop and animal production, consumer behaviours, and governmental policies have all affected food sustainability. The accelerated growth of the global population is systematically depleting the renewable natural resources on the planet. As an example of this, water scarcity is becoming a serious challenge for current food production systems (Mancosu et al., 2015). Reducing water usage, electricity/energy consumption, and distances of transportation have been identified as possible mechanisms of action in sustainable food production (Sim et al., 2007).

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To achieve a successful food production system within the framework of sustainability, coordinated efforts among governments, industries, and consumers must take place in society. In this chapter, the definition, importance, benefits, and limitations of sustainable food development will be discussed. From the sustainability of foods in the era of globalization to the emergence of local food movements, this chapter will describe the effects of food production systems on the environment and society. Several factors including the global economy, public health issues, environmental concerns, and consumer behaviours will be covered in this chapter.

1.1.1 Concepts and Definitions of Food Sustainability

To understand food sustainability, a close look at food systems must take place. Food production, processing, transportation, and consumption are all components of food systems. The politics and economics of food production, its sustainability, the amount of food waste, the effects of production on the environment, and the influence of food on public health are all issues connected to food systems (von Braun et al., 2020). During the last decades, the global food system has contributed significantly to climate change-related greenhouse gas emissions, as well as other significant environmental problems such as soil erosion and pollution (Turner & Turner, 2007). As governments around the world become more aware of the seriousness of these problems, they are also facing other significant challenges related to food security and nutrition as they must ensure that enough food is available to satisfy the rising food demand in the societies (Ericksen, 2008). In summary, more consumers will require better foods that have lower environmental and social effects.

The food system is a macro concept, and food sustainability is its derivative. Food sustainability's long-term goal is to generate sufficient food for maintaining human populations. To achieve this, the core factors to ensure sustainable food production systems are having fertile land, freshwater, low-toxicity level fertilizers, stable climates, and less consumption of energy (Morawicki & González, 2018). In other words, sustainable food is food that is grown or farmed in such a manner that its negative impacts on the environment and the communities are minimized. Foods that are ecologically friendly and utilize resources in the most optimal way possible are referred to as sustainable foods. The goal of sustainable food is to lower the carbon and water footprints of the production and manufacturing processes (Seiber, 2011). Minimizing humans' influences on the global environment can be achieved by selecting sustainable food production systems, and this is becoming a challenging issue for governments, industries, and consumers around the world.

1.2 Food Sustainability in the Era of Globalization

1.2.1 Main Challenges in Food Production on a Global Scale

Food production systems vary greatly from region to region around the world. This is one of the main reasons for avoiding singular models in food sustainability. In general, the northern hemisphere of the globe has higher food production quantities than the lower hemisphere. This difference in food production quantities can pose different challenges when adopting various sustainability policies. One of these challenges is to minimize food waste around the world. Food waste is defined as the reduction in the quality of edible foods that are intended for human consumption. It is estimated that 30% of the total food production in the world goes to waste (Rezaei & Liu, 2017). Food waste generation varies in different parts of the world and this problem is becoming a critical concern in regions where food insecurity is prevalent.

A study made by Gustavsson et al. (2011) of food systems around the world showed that food production (total per capita) was higher in the European and North American regions compared to that of the Sub-Sahara African and South/Southeast Asian regions (900 vs. 460 kg/year).

A more extreme difference between these two regions was recorded for the food waste per capita parameter, in which higher quantities were observed for North American and European consumers compared to those of sub-Sahara African and South/Southeast Asian consumers (95–115 vs. 6–11 kg/year) (Gustavsson et al., 2011). On the other hand, higher differences were also found in the total per capita food loss during production in North America and Europe compared to that of Sub-Saharan Africa and South/Southeast Asia (280–300 vs. 120–170 kg/year).

In general, total food waste and losses in industrialized countries (such as the USA or countries in Europe) were as high as compared to those in developing countries (Africa and Asia) relative to their total production volumes. However, differences arise when comparing the type of food waste in each region. In developing countries, almost 40% of the food waste takes place at some stage of the industrial processing chain (post-harvesting, manufacturing), while almost 40% of the food waste occurs at the market and/or consumer levels in industrialized countries (Gustavsson et al., 2011). In other words, when production exceeds demand, food will be discarded and become waste in industrialized countries. Food waste has serious negative impacts on society and the environment. It is estimated that the value of food waste per year around the world is US$ 1 trillion. Food waste can raise food prices in supermarkets and decrease the capacity of low-income buyers to access foods (Rezaei & Liu, 2017).

1.2.2 The Relationship Between Climate Change and Food Production

Climate change's relative importance to food production and security varies from region to region around the world. For instance, the climate in Southern Africa is one of the most significant drivers of food insecurity. Temperatures are expected to continue increasing which can cause extreme weather conditions for this region. Changes in temperature and rainfall could cause some areas in the African region to become warmer and wetter, while other areas to become warmer and drier (Mpandeli et al., 2018). Climate change can have significant direct and indirect effects on food production and even threaten public health. By having immediate effects on the annual precipitation rates, extreme weather events, and the rising average annual temperatures, climate change can rapidly modify our current food production system models. In the long term, climate change can affect the production of plants and animals, which might have to adapt to warmer weather conditions (Vermeulen et al., 2012). These effects can be accompanied by risks of food contamination due to the growth of bacteria, viruses, parasites, harmful algae, fungi, and toxic pollutants (Tirado et al., 2010). Changes in local fauna and flora can also affect the usage of pesticide and veterinary drug residues in animal and plant products. The contamination of foods by heavy metals and organic pollutants can occur due to drastic changes in weather conditions. Climate changes can affect food production by having massive redistributions in the cultivation of crops, a decrease in cultivated plant varieties, the constant erosion of soils, and massive migration of different animal species. However, climate change can also be the cause of reduction in the environmental concentration of pesticides in the long term due to the volatization and degradation of pollutants under higher amounts of precipitation and erosion (Delcour et al., 2015).

Overall, changes in the current food production system can be associated with risks in food safety and food security. Current production models in developing countries are very fragile and vulnerable to changes in the environment. Climate change can lead to the emergence of food-related diseases and malnutrition. On the other hand, the risks associated with climate change are highly variable as some countries will experience an increase in food production volumes in the upcoming decades, while others will suffer from food insecurity (Vermeulen et al., 2012). Therefore, individual national policies should be developed to cope with the variable effects of climate change on food production systems. For instance, climate change will dramatically affect the food production system in Vietnam (Rutten et al., 2014). The delta structure on the long coast of Vietnam is highly sensitive to flooding and extreme weather conditions. These make the Vietnam population extremely vulnerable in terms of food security and food safety due to the drastic changes in the environment. At the same time, another key factor in play to explain the complexities of climate change is understanding the macroeconomic structures of Vietnam and its population. The gross domestic product (GDP) of Vietnam has rapidly increased over the last decade, averaging 6–8% annually. As a consequence of this, increases in greenhouse gas (GHG) emissions have been seen in the country as well, of which almost half of the emissions are attributable to agriculture (the main production crop is rice) and land usage. It is expected that the production yield of key crops will be diminished due to the rapid effects of climate change (Rutten et al., 2014). There are scenarios similar to what is happening in Vietnam in various countries around the world. National and international organizations must plan future activities to mitigate the effects of climate change on food production systems.

1.2.3 Climate Change on Food Safety and Security

Climate change directly affects the weather parameters (such as temperature and humidity) in global and specific regions. These changes can have a drastic effect on the growth of bacteria, viruses, and pathogens. Also, water and soil pollution can occur with significant changes in the environment. In addition, temperature, humidity, and precipitation changes can lead to the flowing of fertilizer nutrients into water sources (rivers, lakes, oceans), becoming a "catalyst" for the blooming of algae around the world. Therefore, climate change might promote the proliferation of pathogenic microorganisms and the appearance of foodborne diseases in several countries. Non-refrigerated foods are the most susceptible to spoilage (due to the growth of bacteria and fungi) under the current climate change conditions (Misiou & Koutsoumanis, 2021).

For animal production systems, climate change can cause an increase in the appearance of zoonotic diseases. Moreover, pathogenic microorganisms can adapt to new environmental conditions, which can change their survival rates. Therefore, increases in the dosage of veterinary drugs will be necessary, which may lead to increases in drug residues in animal-derived foods. This can lead to acute and chronic risk problems associated with human health. Moreover, drug residues are the leading cause of pathogens' resistance in the long term (Caminade et al., 2019). Changes in rainfall patterns and soil erosion can dramatically change the movement of pesticide residues in the environment. Floodings and changes in the courses of rivers can produce sediment pollution, which can contaminate soils, farmlands, pastures, and the environment in general. This leads to finding biological and chemical hazards in foods, which are combined with the uncertainties of the overall production yields from farmers. All these factors contribute to challenging the supply of food to vulnerable communities. Populations in places that experience food insecurity are at risk of malnutrition and several food-related diseases (Vermeulen et al., 2012).

1.2.4 Local Food Movements

It is generally believed that locally produced foods have lower negative environmental impacts than foods grown, harvested, and transported from long-distance locations (Striebig et al., 2019). However, the size of the environmental effects is dependable on the type of transportation. As a rough estimation, faster and low-capacity transportation methods tend to have greater environmental effects (such as transporting premium food products by plane). Moreover, the type of food can also add variability to the carbon footprint impact; for instance, highly perishable foods such as vegetables, fruits, meats, and seafood require transportations that are equipped with refrigeration, which can have greater negative effects on the environment compared to other transportation methods (Konieczny et al., 2013). On the other hand, food products with lower water activity such as grains or dried legumes can be transported in containers that require less expensive conditioning (usually these need to be controlled for relative humidity).

Another factor that needs to be considered when evaluating local foods is the climate and seasonality of different countries. Consumers nowadays are demanding seasonal foods all year round. However, the production of foods is seasonal and depends on the climate conditions. In countries located in the northern and southern parts of the hemisphere, far away from the equatorial region, fruits and vegetables tend to have lower yields during cold seasons. In some cases, it is not possible to grow fruits and vegetables on open farmland. Producers tend to use greenhouses for production, or retailers buy transported foods from other warm regions, but such approaches lead to increased environmental pressure. Fruits and vegetables grown in greenhouses need to be supplemented with light and heat to achieve the ideal growth state. The use of greenhouses to grow crops in large areas in winter can lead to the consumption of a large amount of energy and greenhouse gas emissions.

1.3 Consumer Behaviours Towards Sustainability

Consumers have their own perceptions of food sustainability, which frequently incorporate different notions such as social responsibility, animal wellbeing and/or welfare, fair trade and/or labour, local agriculture, and organic and/or natural food production systems (Peano et al., 2019). Consumers are progressively being more aware of sustainability issues related to food production systems, including having different perceptions about the types of packaging used (paper, cardboard, metal, plastic, or glass) and the information that these packagings reflect (for instance, products labelled as friendly with the environment) (Otto et al., 2021). Food mileage, the distance that food has to travel from the production site to the consumption location, is another concept that is frequently associated with food sustainability by consumers. In some cases, consumers can express concerns about high mileage foods as they associate transportation with pollution (Naspetti & Bodini, 2008). Food sustainability, in broader terms, is defined as the production of foods at a level that is adequate to support the population (Morawicki & González, 2018). However, this definition can vary according to the different perceptions of consumers. In general, concepts such as fertile land, clean water, responsible usage of nutrients, and favourable climate conditions as the foundations of long-term food production have been promoted as pillars of food sustainability.

1.3.1 Factors That Affect Consumers' Behaviours

Behaviours around food choices are complex and dynamic (Köster, 2009). Several factors affect the selection of foods by consumers, such as the sensory properties and extrinsic cues shown by the product. The traditional sensory evaluation of foods focuses on intrinsic factors such as appearance, aroma, taste, texture, and aftertaste (Lawless & Heymann, 2010). However, consumers' expectations of foods based on extrinsic cues, such as the information that is paired with the product (for instance, sustainability or animal welfare), are drastically different compared to the expectations of these products based exclusively on intrinsic sensory attributes (Napolitano et al., 2010). In some cases, consumers who have very limited knowledge about agricultural practices can support sustainability based on their constructed perceptions of production systems. That is, their decisions can be solely explained by trends shown in regular media outlets (TV or online news) and social media. This creates a conceptual dissonance between the actual production practices and the general perception of consumers. For instance, consumers might want to see an increase in positive animal welfare in farms that produce animal products. However, they might not know that increasing these animal activities can generate an increase in greenhouse gas emissions and a higher depletion of natural resources (Garnett et al., 2013), depending on the practices that are implemented in the farms. Food perception can be deeply affected by the type of information that is shown to consumers. In some cases, these perceptions can also affect the overall acceptability of the products (Jiang et al., 2021).

1.3.2 Consumer Behaviours Affecting Food Waste at the Retailers' Level

Food waste in middle or high-income countries is mainly associated with the lack of coordination among different participants in the supply chain. The disagreements in sales and purchases of products by farmers and retailers may result in substantial amounts of food being wasted. Quality standards such as rejecting foods with imperfections (shape or appearance) may cause higher rates of food waste at processing facilities. Consumers might also reject the products at the retailers' locations due to imperfections and lack of sensory appeal (Göbel et al., 2015). Another major food waste factor at the retailers' point of sale is related to the perception of offering "visual abundance" to consumers. Retailers at supermarkets tend to continuously restock fresh produce and other perishable food items to create the impression of abundance that can incentive the increased purchasing behaviours of consumers. However, this practice can lead to food waste if the items are not purchased before the closing time of the stores (de Moraes et al., 2020). However, retailers, nowadays, have been adopting different strategies to divert food waste from landfills. Concerns of consumers and retailers for the environment are the key drivers for the movement of food waste reduction. However, these policies need to offer the required training and education to be successful (Goodman-Smith et al., 2020). Other causes of food waste at the retailers' level include the lack of communication, lack of operational controls, inappropriate work procedures, lack of integrated computerised systems, inadequate demand forecasting, unexpected excess in production, lack of waste measurements, inadequate packaging, and the short shelf life of some products (de Moraes et al., 2020).

The current globalized food systems make the distance between producers and consumers larger; that is, consumers, nowadays, are not aware or they lack the complete knowledge of the current agricultural production practices. In this context, retailers are becoming the main channels for food exposure and information. To maintain the homogeneity of the process and, at the same time, to keep uniform quality control measurements, retailers have sought to standardise food products. For instance, retailers have standard measurements regarding the weight, shape, and size of fresh produce. This can generate food waste at the recollection of these products since these are rejected for not meeting the required standards. These practices have created the artificial perception by consumers that this fresh produce (those that do not have the required size or shape) is of inferior quality in terms of safety and taste (Makhal et al., 2021). In this regard, several solutions have been implemented to deal with food waste caused by sub-optimal products at the retailers' level. The production of derivate products from those sub-optimal raw materials is commonly used by producers who want to avoid waste and gain some profit in the process. Fruits and vegetables that do not meet the standards can be transformed into juices and other processed products. Some sub-optimal products can be sold in "fresh market" places, where consumers are looking to buy fresh foods directly from the producers (Hermsdorf et al., 2017). Usually, the artificial perception of having a perfect shape and size is minimized when the products can be sold directly from the farmers that grow these products. The implementation of alternative processing and commercialization pathways are required to minimize waste in current food production systems, especially for fresh foods that have a shorter shelf life.

1.4 Effect of Food Production on Sustainability

Sustainable agriculture practices are paired with sustainable food production systems. In general, much of the food waste is created in the final steps of agricultural production (for instance, crop harvesting or animal slaughtering) and the beginning of the food processing systems (quality selection and packaging). It is estimated that around one-third of food is lost or wasted globally, which equals approximately 1.3 billion tons per year (Timmermans et al., 2014). However, there are profound discrepancies in how this food waste is generated, which largely depends on the region or country where the food production is located. In this regard, food waste in low-income countries largely occurs in the early and middle stages of the food supply chain. This means that lower quantities of food are wasted at the consumer level. However, in middle and high-income countries, food is largely wasted in the consumption stage, which means that consumers are more responsible for food waste than food industries (Gustavsson et al., 2011). Other important factors affect sustainability within food production systems, including carbon and water footprints and pollution.

1.4.1 Environmental Issues

With the rapid increase of the human population, the steady growth of the global economy and international trade, and the rapid expansion of human cities, the forests, wetlands, and earth's soils have been progressively deteriorating more than ever. The ever-increasing commercial needs of different countries have been coupled with the rapid generation of trash and waste around the world. Today's societies demand a rapid production of foods, which is affecting the land use patterns and employment of natural resources in each country. Modern production systems are replacing grasslands with dense crops, substituting native woodlands with edible or grazing plants to supply populations with the food they need. This situation is happening in several regions of the world, and each country is currently dealing with some of the negative consequences of these practices (floods, fires, soil dryness). A similar effect occurs in the ocean. Sealife is being overfished as never before and the live coral coverage on coral reefs has been greatly reduced. However, the food demand of the growing global population is still increasing, especially for meat and fish. Therefore, there is a substantial resource unbalance between the current food production systems and the natural sustainability of the environment (García-Oliveira et al., 2022).

1.4.1.1 Carbon Footprint (CF)

Carbon footprint (CF) refers to the total amount of greenhouse gas emissions (GHG), which are derived from the manufacturing of products or the provision of services. In food production, the carbon footprint is defined as the total GHG that is generated during the agricultural practices and post-harvesting processes. The GHG includes carbon dioxide, methane, nitrous oxide, and fluorinated gases (East, 2008). The measurement of CF has been recognized as a central indicator of GHG emissions from different companies, organizations, communities, and countries (Wright et al., 2011). Besides, CF has become a selling factor for food and beverages companies, which are becoming aware of the importance of this label in the mind of consumers.

In animal husbandry, the impact of ruminants on the carbon footprint should not be underestimated. Higher measurements of CF have been found in the production of major ruminant species including cattle, sheep, and goats (Henderson et al., 2018). Ruminants emit large amounts of methane through hiccups and small amounts of methane through flatulence. Ruminants have four stomachs, where feeding is digested. Ruminants consume forage or grains. After initial chewing and swallowing, the food returns to the mouth again to be chewed in a process that is called "regurgitation". This approach allows them to digest the feeding better. Ruminants' stomachs are full of bacteria that help digestion; however, a byproduct of this process is the production of large amounts of methane (Jentsch et al., 2007).

In food production systems, other causes of higher CF include transportation, industrial activities, waste management, and other manufacturing activities. Besides, there are also indirect or secondary CF emissions that are derived from the whole lifecycle of products and services associated with the food production systems. For instance, some food products are not immediately consumed, and they have to be stored in certain conditions to maintain their shelf-life. The storage (for instance, freezing or refrigeration) of those products can increase the CF in those production models (Kenny & Gray, 2009). Food industries around the world are investing large amounts of money in estimating the total CF that is emitted by their production systems. This can help to create CF reduction models that can be aligned with the industry and government goals in terms of carbon emissions. Moreover, food companies are also aware of the importance that consumers are giving to the CF labels in products. This can also be viewed as a point of differentiation of these companies from the rest of the market.

1.4.1.2 Water Footprint (WF)

The water footprint (WF) is defined as the water volume used to produce a unit of a specific product or service (m^3/t). Also, WF is defined as the volume of water per year that is consumed in a specific area by an individual or community (m3/yr.) (Lovarelli et al., 2016). For most parts of the world, water security, which is linked to climate change, is a growing problem. It undermines food security as food production systems depend on water inputs. After the industrial revolution, rivers and underground reserves started to be depleted due to urban and industrial transformations in various locations around the world. Driven by maximizing profits, several countries relied on growing crops that require higher water inputs; therefore, the WF was higher than the natural water replenishments, which led to droughts and changes in the environment. These problems can be seen in both developed and developing countries as water is a vital natural resource for humans, which is also used for the production of foods. Currently, policies are heavily focused on carbon footprints; however, water footprints should also be analysed and measured. As food security is still a glooming concern, industries and governments around the world should invest in technologies to countermeasure higher WF in food production systems (Hoekstra & Mekonnen, 2012). Consumers are demanding products that can be friendly to the environment. That is, consumers are pushing industries to adopt different production practices. For instance, the meat industry has been under pressure to optimize its production to reduce CF and WF (Muthu, 2019). Other industries are following the same path. Although they are prioritizing CF, WF is intrinsically connected with carbon emissions. Therefore, an integral approach (including CF, WF, food waste, pollution, and other environmental factors) is recommended when measuring sustainability in different food production models.

1.4.1.3 Pollution

With the development of Western industrialization in the twentieth century, rapid agricultural developments have been shaping current food production systems. Since the 1970s, developed countries have rapidly optimized modern agriculture based on mechanization, industrial transformation, and energy conversion as its main drivers (Evans & Lawson, 2020). The large-scale usage of machinery, fertilizers, pesticides, and herbicides increased the land and labour productivity, which caused a rapid expansion of the population. However, a series of undesirable consequences were also the results of these rapid expansions, including environmental pollution, soil erosion, ecological damage, simplification of animal and plant species, and loss of germplasm resources. Increased applications of chemical fertilizers and pesticides not only pollute the soil environment and crops but also affect humans' health and food safety (Campagnolla et al., 2019). It is estimated that agricultural practices are responsible for 19–29% of the global greenhouse gas emissions. Moreover, agriculture pollutes 70% of the freshwater resources in the world. In the last decades, governments have been introducing different legislations regarding sustainable food production systems. However, their outcomes varied largely from region to region (Zhang et al., 2021). These policies need to be supported by environmental research that can measure and optimize the different agricultural practices to avoid long-term damages to the environment and society.

1.5 Public Health

Food sustainability and public health are inextricably linked (Ogden et al., 2014). Weight gain and obesity are the results of more calories consumed than expended in activities such as sports. The majority of foods cause weight gain, but the main culprit can be attributed to high-calorie foods. The growing obesity pandemic poses another challenge to the sustainability of agriculture. For instance, the consumption of considerable amounts of meat products is strongly correlated with the occurrence of several diseases such as obesity, diabetes, and heart-related disease. In this regard, reducing meat consumption and increasing the levels of dietary protein obtained from high-protein plant foods (legumes, cereals, and tubers) are associated with different human health and ecological benefits (Ripple et al., 2013).

Overweight and obesity have major implications for humans' health and the environment. Being overweight reduces physical activity and personal mobility, which results in a continuous accumulation of fat. In addition to expanding food production to adapt to the growing population, agriculture is under the pressure of producing extra food, which is associated with the overweight population. This not only puts pressure on non-renewable arable land resources but also increases the severity of other environmental problems, such as water resources. In this regard, consumers are becoming more aware of how food is a crucial factor in health and the environment. More consumers are now demanding healthier foods that can also be environmentally friendly. This is challenging current food production systems and now some industries are aiming for drastic changes in their production models.

Consumers' environmental demands are also reflected in animal husbandry. In addition to the health effects, diets have also different effects on the environment. With the effects of globalization, consumers' consumption of animal protein has increased. This phenomenon drove farmers to raise more livestock and produce more animal products. This increase in animal production has led to increases in soil erosion, water depletion, pollution, impacts on biodiversity, and interference with nitrogen and carbon cycles (Milford et al., 2019). Changes in food production are driven by consumers' demands; therefore, industries and governments need to implement policies that can show consumers the benefits of sustainable agricultural practices that are coupled with the production of healthy and nutritious foods.

1.6 Conclusion

Sustainability has been a key focus of governments and industries as food production systems are facing huge challenges in providing better foods for humans that can also be better for the environment. Some of these changes are driven by technological innovations. However, this must be aligned with adequate policies and legislation. For instance, developed countries should implement policies regarding reducing food waste in the later stages of the food production chain, requiring retailers and restaurants to take action to minimize and reuse waste. On the other hand, consumers also need to act regarding their lifestyles and behaviours. For instance, consumers need to learn more about how to buy and prepare foods, learn how to buy in moderation, and reduce excessive demand for food if it is not needed. Conversely, policies and comprehensive support are needed to improve technology and help farmers grow healthy and sustainable foods. However, a coordinated effort among governments, industries, and consumers is required to adopt this food production model.

References

Caminade, C., McIntyre, K. M., & Jones, A. E. (2019). Impact of recent and future climate change on vector-borne diseases. *Annals of the New York Academy of Sciences, 1436*(1), 157–173.

Campagnolla, C., Rametsteiner, E., & Gutierrez, D. (2019). Sustainable agriculture and food systems: Towards a third agricultural revolution. *From Fome Zero to Zero Hunger, 140*.

de Moraes, C. C., de Oliveira Costa, F. H., Pereira, C. R., da Silva, A. L., & Delai, I. (2020). Retail food waste: mapping causes and reduction practices. *Journal of Cleaner Production, 256*, 120124.

Delcour, I., Spanoghe, P., & Uyttendaele, M. (2015). Literature review: Impact of climate change on pesticide use. *Food Research International, 68*, 7–15.

East, A. J. (2008, September 26). *What is a carbon footprint? An overview of definitions and methodologies.* Paper presented at the Vegetable industry carbon footprint scoping study—Discussion papers and workshop

Ericksen, P. J. (2008). Conceptualizing food systems for global environmental change research. *Global Environmental Change, 18*(1), 234–245.

Evans, J. R., & Lawson, T. (2020). From green to gold: Agricultural revolution for food security. *Journal of Experimental Botany, 71*, 2211–2215.

García-Oliveira, P., Fraga-Corral, M., Pereira, A., Prieto, M., & Simal-Gandara, J. (2022). Solutions for the sustainability of the food production and consumption system. *Critical Reviews in Food Science and Nutrition, 62*(7), 1765–1781.

Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., et al. (2013). Sustainable intensification in agriculture: premises and policies. *Science, 341*(6141), 33–34.

Göbel, C., Langen, N., Blumenthal, A., Teitscheid, P., & Ritter, G. (2015). Cutting food waste through cooperation along the food supply chain. *Sustainability, 7*(2), 1429–1445.

Goodman-Smith, F., Mirosa, M., & Skeaff, S. (2020). A mixed-methods study of retail food waste in New Zealand. *Food Policy, 92*, 101845.

Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., & Meybeck, A. (2011). *Global food losses and food waste*. FAO Rome.

Henderson, B., Golub, A., Pambudi, D., Hertel, T., Godde, C., Herrero, M., et al. (2018). The power and pain of market-based carbon policies : a global application to greenhouse gases from ruminant livestock production. *Mitigation and Adaptation Strategies for Global Change, 23*(3), 349–369. https://doi.org/10.1007/s11027-017-9737-0

Hermsdorf, D., Rombach, M., & Bitsch, V. (2017). Food waste reduction practices in German food retail. *British Food Journal*.

Hoekstra, A. Y., & Mekonnen, M. M. (2012). The water footprint of humanity. *Proceedings of the National Academy of Sciences, 109*(9), 3232–3237.

Jentsch, W., Schweigel, M., Weissbach, F., Scholze, H., Pitroff, W., & Derno, M. (2007). Methane production in cattle calculated by the nutrient composition of the diet. *Archives of Animal Nutrition, 61*(1), 10–19.

Jiang, R., Sharma, C., Bryant, R., Mohan, M. S., Al-Marashdeh, O., Harrison, R., & Torrico, D. D. (2021). Animal welfare information affects consumers' hedonic and emotional responses towards milk. *Food Research International, 141*, 110006.

Kenny, T., & Gray, N. (2009). Comparative performance of six carbon footprint models for use in Ireland. *Environmental Impact Assessment review, 29*(1), 1–6.

Konieczny, P., Dobrucka, R., & Mroczek, E. (2013). Using carbon footprint to evaluate environmental issues of food transportation. *LogForum, 9*(1).

Köster, E. P. (2009). Diversity in the determinants of food choice: A psychological perspective. *Food Quality and Preference, 20*(2), 70–82.

Lawless, H. T., & Heymann, H. (2010). *Sensory evaluation of food: Principles and practices*. Springer.

Lovarelli, D., Bacenetti, J., & Fiala, M. (2016). Water footprint of crop productions: A review. *Science of the Total Environment, 548*, 236–251.

Makhal, A., Robertson, K., Thyne, M., & Mirosa, M. (2021). Normalising the "ugly" to reduce food waste: Exploring the socialisations that form appearance preferences for fresh fruits and vegetables. *Journal of Consumer Behaviour, 20*(5), 1025–1039.

Mancosu, N., Snyder, R. L., Kyriakakis, G., & Spano, D. (2015). Water scarcity and future challenges for food production. *Water, 7*(3), 975–992.

Milford, A. B., Le Mouël, C., Bodirsky, B. L., & Rolinski, S. (2019). Drivers of meat consumption. *Appetite, 141*, 104313.

Misiou, O., & Koutsoumanis, K. (2021). Climate change and its implications for food safety and spoilage. *Trends in Food Science & Technology*.

Morawicki, R. O., & González, D. J. D. (2018). Focus: Nutrition and food science: Food sustainability in the context of human behavior. *The Yale journal of Biology and Medicine, 91*(2), 191.

Mpandeli, S., Naidoo, D., Mabhaudhi, T., Nhemachena, C., Nhamo, L., Liphadzi, S., et al. (2018). Climate change adaptation through the water-energy-food nexus in southern Africa. *International Journal of Environmental Research and Public Health, 15*(10), 2306.

Muthu, S. S. (2019). Environmental water footprints. Agricultural and Consumer Products. *Springer*. Hong Kong. 45–74.

Napolitano, F., Braghieri, A., Piasentier, E., Favotto, S., Naspetti, S., & Zanoli, R. (2010). Effect of information about organic production on beef liking and consumer willingness to pay. *Food Quality and Preference, 21*(2), 207–212.

Naspetti, S., & Bodini, A. (2008). Consumer perception of local and organic products: substitution or complementary goods? *The International Journal of Interdisciplinary Social Sciences, 3*(2), 111–122.

Ogden, C. L., Carroll, M. D., Kit, B. K., & Flegal, K. M. (2014). Prevalence of childhood and adult obesity in the United States, 2011-2012. *JAMA, 311*(8), 806–814. https://doi.org/10.1001/jama.2014.732

Otto, S., Strenger, M., Maier-Nöth, A., & Schmid, M. (2021). Food packaging and sustainability–consumer perception vs. correlated scientific facts: A review. *Journal of Cleaner Production, 298*, 126733.

Peano, C., Merlino, V. M., Sottile, F., Borra, D., & Massaglia, S. (2019). Sustainability for food consumers: Which perception? *Sustainability, 11*(21), 5955.

Rezaei, M., & Liu, B. (2017). Food loss and waste in the food supply chain. *International Nut and Dried Fruit Council: Reus*, pp. 26−27

Ripple, W. J., Smith, P., Haberl, H., Montzka, S. A., McAlpine, C., & Boucher, D. H. (2013). Ruminants, climate change and climate policy. *Nature Climate Change, 4*(1), 2–5. https://doi.org/10.1038/nclimate2081

Rutten, M., van Dijk, M., van Rooij, W., & Hilderink, H. (2014). Land use dynamics, climate change, and food security in Vietnam: A global-to-local modeling approach. *World Development, 59*, 29–46. https://doi.org/10.1016/j.worlddev.2014.01.020

Seiber, J. N. (2011). Sustainability and agricultural and food chemistry. *Journal of Agricultural and Food Chemistry, 59*, 1–21.

Sim, S., Barry, M., Clift, R., & Cowell, S. J. (2007). The relative importance of transport in determining an appropriate sustainability strategy for food sourcing. *The International Journal of Life Cycle Assessment, 12*(6), 422–431.

Striebig, B., Smitts, E., & Morton, S. (2019). Impact of transportation on carbon dioxide emissions from locally vs. non-locally sourced food. *Emerging Science Journal, 3*(4), 222–234.

Timmermans, A., Ambuko, J., Belik, W., & Huang, J. (2014). *Food losses and waste in the context of sustainable food systems*

Tirado, M. C., Clarke, R., Jaykus, L., McQuatters-Gollop, A., & Frank, J. (2010). Climate change and food safety: A review. *Food Research International, 43*(7), 1745–1765.

Turner, N. J., & Turner, K. L. (2007). *Traditional food systems, erosion and renewal in Northwestern North America*

Vermeulen, S. J., Campbell, B. M., & Ingram, J. S. (2012). Climate change and food systems. *Annual Review of Environment and Resources, 37*, 195–222.

von Braun, J., Afsana, K., Fresco, L., Hassan, M., & Torero, M. (2020). Food systems–definition, concept and application for the UN food systems summit. *Science Innovation, 27*.

Wright, L. A., Kemp, S., & Williams, I. (2011). 'Carbon footprinting': Towards a universally accepted definition. *Carbon Management, 2*(1), 61–72.

Zhang, R., Ma, W., & Liu, J. (2021). Impact of government subsidy on agricultural production and pollution: A game-theoretic approach. *Journal of Cleaner Production, 285*, 124806.

2 Carbohydrates for Energy

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Abstract

Carbohydrates are the most common source of energy for humans. Among this class of macronutrients, starch and sugar are the main representatives. Starches of different types can be obtained from tubers and grain-based foods such as cereals, legumes, pasta and noodles. Sugars can be extracted from plants or eaten as part of a wholesome food, typically fruits and milk. Nutritionally, low glycemic index offers the best long term health effects. That means choosing less refined food products (wholegrains vs refined; fruits vs. sugar). Processing can have a positive impact, as in the case of pasta vs. bread. Environmentally, grains require more resources than produce, while attracting consumers for their taste and competitive price. Innovations such as malt flour can provide an interesting alternative to other starches. Sugar wise, Stevia can be a sustainable sweetener, yet not providing energy. Upcycled sweeteners from spent grains are low in both glycemic index and carbon footprint, while fruits, sweet vegetables and fibre-rich syrups can be both energizing and environmentally friendly.

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Keywords

Carbon footprint · Fruits · Glycemic index · Starch · Sugar · Wholegrains

2.1 Starch and Sugar as Source of Energy

Humans need energy to live. Food offers multiple sources of energy, in the form of lipids, protein and carbohydrates. While lipids deliver the highest caloric intake (9 kcal/g vs. 4 kcal/g of carbohydrates and protein), carbohydrates represent the most abundant source of energy in most diets (NIH, 2021; USDA, 2021). This is due to the higher carbohydrate content of most foods, particularly grains and starchy roots, followed by dairy. Dietary carbohydrates are a diverse group of nutrients, ranging from very simple structures (simple sugars like glucose and fructose), to disaccharides (sucrose, also known as table sugar), to starch. Starches have various degree of resistance to human digestion, resulting in different times of glucose release. It is important to observe that not only quantity and quality of carbohydrates affect how quickly they are digested, but also food composition. Factors like protein, lipid and fibre content, as well as physical

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Fig. 2.1 Representative sources of starch: traditional (rice) and innovative (potato starch)

structure, affect glucose release (Scazzina et al., 2016; Smith et al., 2017). A common way to analyse carbohydrate quality is by measuring the glycemic index: the speed at which glucose is release from a food product and it will be discussed as one of the key parameters. Multiple tests have been proposed to measure glucose release after a meal, with glycemic index considered as useful by numerous health agencies (Scazzina et al., 2016). The unit of measurement that is used to measure the quality of carbohydrate is Glycemic Index (GI). Glycemic Index refers to a scale that measures how quickly a food product causes a person's blood sugar to rise. Foods can be classified into three categories based on their GI values: high-GI foods (>70), intermediate-GI foods (>55−70), and low-GI foods (<55) (Eleazu, 2016). A high GI indicates that the carbohydrate in a food product is absorbed more quickly into the blood sugar. It's hard to measure the accurate GI of a food product as GI varies a lot depending on several factors such as the physical form of the food product (a mashed cube of potato can have 25% higher GI than an unmashed cube of potato), the type of the food product, the way the food product is processed and prepared, and the content of other macronutrients in the food product (protein, fat, fiber) (Pi-Sunyer, 2002). A slow glucose release is desirable since it provides satiety and prevents diabetes (Willett et al., 2002). An exception to this is represented by athletes who might look for fast release during their performance. Each food source has a different impact on the environment, requiring water and emitting carbon as a result of growing raw materials, processing into foods and distribution. Finally, nutrition and sustainability are not achieved without pleasant taste and affordable prices.

Therefore, this chapter will focus on starch and sugar as source of energy. Authors would like to emphasize that carbohydrates are not the only source of energy, but are presented separately in this chapter since it's the goal of this book to treat one nutrient at a time. Representative food sources of these nutrients will be presented for their nutritional value, environmental impact, and consumer acceptance. Traditional and innovative foods will be discussed, to offer the reader with a comprehensive toolset to make informed decisions when choosing a carbohydrate-based source of energy. An example of the modern trajectory of lipid-rich food products is depicted in Fig. 2.1.

Table 2.1 Representative food sources of starch: products, nutritional value (quantity, quality), sustainability (water and carbon footprint) and consumer acceptability (price, sensory)

	Nutrition		Sustainability		Acceptability	
Food products	Starch quantity (g/100 g)	Starch quality (GI)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory profile
Corn Flakes	84	93	1,222 (corn)	1.26 (corn flour)	0.66	Crispy, sweet
	USDA (2020)	USDA (2020)	Mekonnen and Hoekstra (2012)	Xu et al. (2017)	Countdown (2021)	Chaunier et al. (2005)
Rice Noodles	80	53	2,500 (rice)	1.20 (rice)	0.84	White translucent colour, rice fragrance, sticky, chewy, delicate taste
	USDA (2013a, b)	Atkinson et al. (2008)	Mekonnen and Hoekstra (2012)	Xu et al. (2020)	Countdown (2021)	
Buckwheat Noodles (Soba)	75	56	3,463	1.91 (buckwheat flour)	1.18	Dark colour, hard, chewy, slightly bitter aftertaste
	USDA (1989)	Wee and Henry (2020)	Mekonnen and Hoekstra (2010)	Xu et al. (2017)	Countdown (2021)	
Pasta	72	48	1,336–2,847	0.18–0.49	0.50	Yellow, Slight nutty smell, firm
	Vernaza et al. (2012)	Atkinson et al. (2008)	Ruini et al. (2013)	Cimini et al. (2019)	Countdown (2021)	
Rolled Oats	68	55	2,416	0.55	0.28	Dry, soft, light taste
	USDA (2020)	Atkinson et al. (2008)	Mekonnen and Hoekstra (2010)	Heusala et al. (2020a, b)	Countdown (2021)	
Wholemeal Bread	38	74	1,300	1.18	0.28–0.49	Dark brown, wheat aroma, nutty flavour
		Food Composition Data (2019)	Mekonnen and Hoekstra (2010)	Chiriacò et al. (2017)	Countdown (2021),	

2.2 Traditional Food Sources of Carbohydrates

2.2.1 Starch

Six representative food products were chosen as sources of starch: breakfast items like corn flakes and rolled oats, as well as staple foods like rice noodles, buckwheat (Soba) noodles, pasta and wholemeal bread (Table 2.1).

The quantity of starch found in these products varied from 38 g/100 g of wholemeal bread to 84 g/100 g of corn flakes (USDA, 2020). However, after the noodle products are cooked, the carbohydrate content in each product is found to have decreased significantly with rice noodles having only 24 g/100 g, buckwheat noodle 27 g/100 g, and durum wheat pasta with the highest carbohydrate content among the three with 30 g/100 g (Sugiyama et al., 2003; USDA, 2013a, b, 2015). This is the case because when these food products are cooked (boiled in water) most of the starch in them leaches out into the water and especially for rice noodles the amount of starch that leaches out into the water is higher due to the small granule size of the carbohydrates in the noodle; the smaller the size of the molecule, the lower the weight of the molecule resulting in less intermolecular interaction of polysaccharide which will make it more soluble in water and this explains why so much starch is lost during the cooking of rice noodles (Guo et al., 2017; Low et al., 2020).

Pasta has the lowest GI among the three. There have been several studies aiming to determine the reason why pasta has a low GI despite being a starchy, carbohydrate packed food. One study said that pasta's low GI is due to its compact texture, the low degree of mastication before being swallowed and the large solid particles pasta becomes when it reaches the stomach (Kim et al., 2008). Its compact texture and large particle size limit the surface area of available starch that digestive enzymes are able to absorb hence limiting digestion rates. The large particle size also lowers the rate of gastric emptying. Another hypothesis is the presence of a continuous protein matrix that limit the accessibility of starch to α-amylase by trapping the starch granules. This result was in agreement with high GI for bread. Despite a fibre-rich recipe, wholemeal bread still presented a GI of 74 due to its light structure, result of yeast fermentation and baking. Overall, corn flakes represented the richest source of easily digestible starch (GI 93 vs. 48–74 of others), while noodles, pasta and rolled oats delivered similar quantity of starch at a lower speed.

As shown in the table above, the amount of water needed to make 1 kg of durum wheat pasta ranges from 1,336 to 2,847 L of water which is dependent on several factors such as the production site, conditions of the local environment, and the adoption of agricultural techniques used during the cultivation of the durum wheat (Ruini et al., 2013). Although this may seem like a high amount of water consumption, the durum wheat pasta is actually the most sustainable in terms of water consumption compared to the buckwheat noodle which requires 3,463 L of water just to produce 1 kg of buckwheat which means it will use up even more water to make 1 kg of the buckwheat noodle (Mekonnen & Hoekstra, 2010). Rice noodle is in between the durum wheat pasta and the buckwheat noodle in terms of water consumption with 2,500 L of water needed to grow 1 kg of rice but this also means more water will be needed to use the rice and turn them into rice noodle. The lowest water footprint was recorded for bread, although this might be due to its lower solid content.

In order to obtain a big picture, carbon footprint was examined, as an indicator of polluting emissions derived from food manufacturing. Interestingly, pasta production resulted in significantly lower carbon emissions than the other food examine: 0.18–0.49 kg CO_2/kg product vs. 0.55–1.91 kg CO_2/kg product (Table 2.1). Carbon emissions are the result of processing, distribution and transportation. From an environmental standpoint, pasta seems a more sustainable source of carbohydrates when compared to rice, corn and oat products. Results vary based on location and supply chain. High carbon footprint can be the result of low yield of raw material and/or more intensive processing needed to achieve the desired sensory quality.

Speaking of consumer acceptability, price and sensory were investigated. The cheapest product (according to New Zealand stores) is rolled oats, while the most expensive is rice noodles, at about three times the price (Table 2.1). The sensory profile of each food product is quite different from each other. Corn flakes are well known as crunchy and sweet. Noodles, on the other hand, are not crunchy. Buckwheat noodles have dark, brownish/greyish colour due to the presence of hull fragments found in the buckwheat flour used to make the buckwheat noodle (Wronkowska & Haros, 2014). Aside from its hard and chewy texture, buckwheat noodle is also known to possess a relatively high tensile strength and low extensibility which means it is stretchy (Ikeda et al., 2001). A research comparing buckwheat noodles made from common buckwheat and Tartary buckwheat found that buckwheat noodles made from Tartary buckwheat tasted more bitter than the ones made from common buckwheat; the noodles made from Tartary buckwheat also have a slightly bitter aftertaste (Starowicz et al., 2018). Rice noodles have a white, translucent colour and a clear fragrance of rice due to the rice flour used to make them. The cooking process and time affect the final texture of rice noodles; surface moisture gives the rice noodle its sticky texture (Li et al., 2021). To the best of my knowledge, rice noodle does not have a prominent taste nor aftertaste that can be uniquely identified and described. The durum wheat pasta has a yellowish colour which is caused by the natural carotenoid pigment content of the durum wheat and the oxidation of the durum wheat by a group of enzymes called Lipoxygenase (LOX) (Sissons, 2008). The durum wheat also has a nutty taste which gives the pasta a very slight nutty taste but to the best of my knowledge, it does not have any prominent taste nor aftertaste. The texture of durum wheat pasta is also harder and firmer than buckwheat noodle and rice noodle because of the slightly higher protein content in the durum wheat used to make the pasta but this firmness and hardness will vary according to the protein content in the durum wheat used to make the pasta (Sissons, 2008). Rolled oats are quite neutral in taste, while wholemeal bread is dark brown in colour, soft, with wheat aroma and nutty flavour.

2.2.2 Sugar

Sugar can be consumed either as is (extracted from beet or cane) or obtained from foods such as milk and produce. A representative selection includes refined cane sugar, raw cane sugar, milk powder, milk, apple juice and apples (Table 2.2). As expected, the GI of cane sugar is very high, but it is interesting to observe how this value increases when the raw sugar is refined, rising from 69 to 91 (Scazzina et al., 2016). Refined sugar is mostly sucrose, whereas raw sugar contains a mixture of about 95% sucrose and 5% molasses, thus being absorbed more slowly. Dairy is a popular food category, known for protein and lipids, among other nutrients. Some consumer may not realise that the most abundant nutrient in milk is sugar, specifically lactose, representing 40% of the solid fraction and at least 5% of fresh milk (USDA, 2019). The glycemic index is moderate (45 and 41 for powder and fresh, respectively) (Atkinson et al., 2008; Foster-Powell et al. 2002). These values were attributed to the presence of protein and fat, while the slightly higher GI for milk powder can be attributed to the spray-drying process, which reduces particle size, thus enhancing digestibility (Elversson & Millqvist-Fureby, 2005). A good source of sugar is fruit. Taking the example of apples, they contain about 12–13 g/100 g of sugars (USDA, 2019; USDA, 2020), whether it is in the raw form or processed into a juice. What is noteworthy, is the fact that the juice has a significantly higher GI: 41 vs. 36 (Atkinson et al., 2008). This is due to the fact that the juicing process eliminates fibre and other nutrients that allow slow sugar release from the fruit, in addition to represent a nutritional loss. Therefore, despite equal quantity of sugar, raw apples are a better choice than apple juice.

The water footprint of most sugar sources is limited, at around 1,000 L/kg product (Table 2.2). It is interesting to notice that, often, the more processing is required, the more water is consumed, such as in the case of sugar refinement (1,782 vs. 1,666 L water/kg product) and apple juicing (1,141 vs. 822 L water/kg product) (Mekonnen and Hoekstra 2010). The effect of processing becomes more relevant when looking at carbon emissions, with increases in the order of ten-fold. Juicing apples increased the carbon footprint from 0.1 to 1.0 kg CO_2/kg product (Cambridge Carbon Footprint, 2013; Figueiredo et al., 2014) while drying milk lifted this value from 1.0 to 9.0 CO_2/kg product (Flysjö et al., 2014). Juicing and spray-drying both have major environmental impacts, greater than sugar refining (Fig. 2.2).

When looking at consumer acceptability, it is well known how addicting sugar can be, and its low price lures consumers in. Less addicting sources of sugar are milk and produce like apples, other fruits and sweet vegetables. Key sensory differences are represented by dark colour and lower sweetness (raw vs. refined sugar) (Orlandi et al., 2017; Pinto et al., 2021). Milk is well known for its creamy texture and

Table 2.2 Representative food sources of sugar: products, nutritional value (quantity, quality), sustainability (water and carbon footprint) and consumer acceptability (price, sensory)

	Nutrition		Sustainability		Acceptability	
FOOD products	Sugar quantity (g/100 g)	Sugar quality (GI)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory profile
Sugar, refined (100% sucrose)	100	91	1,782	0.2–0.5	0.19	Light color, sweet aroma and flavour
	USDA (2019)	Scazzina et al. (2016)	Mekonnen and Hoekstra (2010)	Rein (2011)	Countdown (2021)	Pinto et al. (2021)
Sugar, cane (95suc 5mol)	100	69	1,666	0.4	0.25	Dark, small granules, less sweet than refined sugar
	USDA (2019)	Scazzina et al. (2016)	Mekonnen and Hoekstra (2010)	Rein (2011)	Countdown (2021)	Orlandi et al. (2017)
Milk Powder	40	45	1,000	9.0	0.95	Sweet, granular
	USDA (2019)	Foster-Powell et al. (2002)	Ridoutt et al. (2010)	Flysjö et al. (2014)	Countdown (2021)	Cooper (1981)
Milk, whole fat	4.8	39	1,000	1.0–1.2 energy corrected)	0.18	Creamy, sweet
	USDA (2019)	Atkinson et al. (2008)	Ridoutt et al. (2010)	Flysjö et al. (2014)	Countdown (2021)	Chojnicka-Paszun et al. (2012)
Apple Juice	13	41	1,141	1.0	0.19	Sour, sweet, clear
	USDA (2019)	Atkinson et al. (2008)	Mekonnen and Hoekstra (2010)	Cambridge Carbon Footprint (2013)	New World (2021)	Okayasuand and Naito (2001)
Apples, Gala	12	36	822	0.1	0.50	Yellow flesh, crispy and juicy texture, sweet
	USDA (2020)	Atkinson et al. (2008)	Mekonnen and Hoekstra (2010)	Figueiredo et al. (2014)	New World (2021)	Corollaro et al. (2013)

sweet taste (Chojnicka-Paszun et al., 2012; Cooper, 1981). Apples vary in flavour based on the cultivar. For example, Gala apples have a yellow flesh, crispy and juicy texture and sweet flavour (Corollaro et al., 2013) while their juice is sour, sweet and clear in appearance (Okayasuand and Naito, 2001). Unfortunately, fresh fruit is expensive. In fact, it is more expensive than juice: 0.50 vs. 0.19 NZD/100 g) (Countdown, 2021). The reason is that short shelf-life costs more money than processing. Therefore, innovative processing that extends shelf-life without nutritional loss is needed. In this sense, fermentation of fruit puree by probiotic bacteria can be a solution, as demonstrated for pear kefir (Hampton et al., 2021).

2.3 Innovative Food Sources of Carbohydrates

2.3.1 Starch

Innovative sources of starch promise to deliver high amounts of carbohydrates with moderate GI and low footprint. Starting from cereals (corn, rice, wheat) and starchy tubers and roots (potatoes, tapioca, yam) novel products are rising (Table 2.3). Rice, tapioca, and yams have been around and consumed for centuries in their original forms or processed into traditional food products such as rice noodles, tapioca flour in baking, and purple yam (ube) flavoured desserts.

Fig. 2.2 Representative sources of sugar: traditional (sucrose) and innovative (date syrup, Stevia)

Table 2.3 Innovative food sources of starch: raw materials, bioavailability (glycemic index) and sustainability (water and carbon footprint)

Products	Raw materials	Bioavailability	Sustainability	
		Glycemic index	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)
Functional chips	Corn	55	1,222	0.48
		Yang et al. (2006)	Mekonnen and Hoekstra (2010)	Zhang et al. (2017)
Malt Flour	Wheat	66	1,827	0.75
		Chaturvedi et al (1997)	Mekonnen and Hoekstra (2010)	Zhang et al. (2017)
Resistant starch	Potatoes	78	287	0.25
		Atkinson et al. (2008)	Mekonnen and Hoekstra (2010)	Svubure et al. (2018)
Rice bran in a tube	Rice	73	2,500	1.3-2.3
		Atkinson et al. (2008)	Mekonnen and Hoekstra (2010)	Xu et al. (2013)
Boba/Tapioca balls	Tapioca	70	3,106	0.56-0.64
		Foster-Powell et al. (2002)	Mekonnen and Hoekstra (2010)	Usubharatana and Phungrassami (2015)
Edible packaging film	Yam	44	343	0.88
		Ampofo et al. (2021)	Mekonnen and Hoekstra (2010)	Go (2009)

However, the world is constantly evolving and developing hence these traditional raw materials are also used in more new and innovative food products.

The Daily Crave chips are made of corn flour that claims clean label and high nutrition. High-quality starch is delivered as well as protein and some micronutrient. Some varieties are gluten-free. By adding up extra vegetable flour and natural condiments that people are familiar with, their taste is also naturally flavoured (Food Navigator USA, 2019). BriesSpecialty malt flour is made of whole wheat flours milled from natural malt. It has non-GMO and clean-labelled ingredients that are from natural materials and used to offer natural colour and flavour adjustment. It only adds malt to increase the whole grain content and lower the GI value. Light colour flour indicates mild to intense flavour and dark flour has a deeper flavour (Food Navigator USA, 2019). The resistant starch derived from potatoes is classified as RS2. It is non-digestible in the small intestine but fermented in the large intestine. It promotes digestive health and insulin and glycaemic response due to the low GI value. Also, it performs well in boosting butyrate, which helps to promote satiety, protect against endothelial dysfunction, and control blood sugar (Food Navigator USA, 2020a, b).

An innovative food product made from rice is the "Nuka" rice bran in a tube packaging made by Kohsei Foods Co., Ltd. This food innovation is targeting the upcycling market trend with more focus on providing more convenience for consumers. It is one form of upcycling because it uses the bran of rice, a part of the rice kernel, which is the by-product of rice milling (Friedman, 2013). Rice bran has been used in food products for some time but this "Nuka" rice bran in a tube can be considered an innovative food product because the packaging it comes in is new and the company only started selling them in January 2021, so it is very recent. The product has been manufactured in a compact and easy-to-use packaging that enables its users to add flavour to their fish or meat in a hygienic way by squeezing the tube packaging. Rice bran is rich in micronutrients like oryzanols, tocopherols, tocotrienols, and phytosterols as well as 15% protein content and 50% carbohydrate dietary fibres like beta-glucan, pectin, and gum (Nagendra et al., 2011). This fermented "Nuka" rice bran improves the health of the intestine which makes it very good for gut health and boosting the immune system (PR Distribution, 2021).

Boba is a pearl-shaped food product made from tapioca that has recently seen an upsurge in demand. Boba's dark colour comes from the brown sugar used to make the balls and is known for its very chewy texture (Min et al., 2017). The global boba drinks market was valued at 5.3 billion USD in 2018 and is estimated to reach 11 billion USD by the end of 2025, implying a CAGR of 9.3% from 2019 to 2025 (Market Watch, 2021a). In April 2021, there have been news saying that there is currently a boba shortage in the United States due to supply chain and logistics disruptions; e-commerce sales of boba have surged due to rising demand but lack of dockworkers and drivers are holding up these boba from getting into the boba drink retailers (Janse, 2021). Boba is entirely plant-based making it vegan-friendly. Boba itself does not have any nutritious value besides being loaded with carbohydrate and sugar, if it was made with sugar, however consumption of boba with tea may contain other nutrients and antioxidant benefits depending on the type of tea used (Min et al., 2017).

An innovative product made from yams is edible film packaging and food coating. In 2020, the global edible films and coating market was valued at 2.6 billion USD and is predicted to grow at a CAGR of 7.64% from 2021 to 2026 (Globe News Wire, 2021). This innovative product is targeting the sustainability market trend because there is an increasing demand to move away from plastics to more sustainable packaging and biodegradable coatings from renewable resources. One experiment done on this yam edible film packaging for food coatings blends purple yam starch, chitosan, and glycerol to create films with homogenous surface and greater thermal stability (da Costa et al., 2020). This edible yam packaging increases the shelf-life of fresh fruits, reducing weight loss and oxidation upon storage (da Costa et al., 2020). However, as this product is still at the early stages of innovation, there is very little information regarding price, sensory, nutritional values, etc. Further research and development on this is definitely something to be looked into as this innovation does have great potential and environmental as well as socioeconomic benefits.

The GI of cooked corn is around 55 (Yang et al., 2006), so it is medium-low GI food. The GI of wheat is 66 (Chaturvedi et al., 1997), which is slightly higher than corn, but still the medium. Boiled potato has a relatively high GI, which counts for 78 (Atkinson et al., 2008). There are few reasons why GI varies. Firstly, potatoes have high starch content in the dry matter, of which 60–80% is starch. Its starch is made of numerous glucose and mainly in the form of amylopectin (Robertson et al., 2018). Also, its fibre content is low, which is about 1.4 g/100 g (Food Composition Data, 2019). Fibre is the component of food that is non-digestible by the human body, thus the low content of fibre increases the GI value. On the contrary, corn and wheat have a much lower GI. Conventionally cultivated wheat contains 60–75% starch (Shevkani et al., 2017), which is slightly lower than that in potato. The composition of the starch is amylose to amylopectin is 0.25:0.75 (Zi et al., 2018). Carbohydrate in cooked corn only counts for 16.7 g/100 g, and its starch is composed of about 25−30% amylose (Amin, 2017), which is even higher than wheat grains. The highest 5 g/100 g fibre among three materials also contributes to the low GI (Food Composition Data, 2019). All the reasons make the potato the highest GI, wheat the medium GI and corn the medium-low GI.

White rice has a high glycaemic index due to its high amylopectin to amylose ratio, post-harvest whitening-polishing, and shorter required cooking time (Boers et al., 2015). Amylopectin is a branched and long polymer of glucose units whereas amylose is a linear and shorter polymer of glucose units. Starches with higher amylose content have a higher gelatinisation temperature which forms complexes with lipids thus reducing the gut enzymes' access to starch (Boers et al., 2015). This means starches with higher amylose content tend to have lower GI values. Tapioca also has a high GI and the reasons for this are similar to the reasons white rice has a high GI. Tapioca has a very low amylose content but a high amylopectin content, similar to white rice, which leads to lower gelatinization temperature making the starch more easily digested and absorbed by the gut into the blood (Charles et al., 2005). Cassava root only has a GI value of 46 when cooked but because tapioca is made by grinding the cassava root into a powder, this increases the surface area to starch ratio which leads to increased rate of digestion thus increasing the GI (Boers et al., 2015; Charles et al., 2005; Nnadi & Keshinro, 2016). Yam has an amylose content of 30%, which is higher than that of rice or tapioca, making it a lower GI food compared to rice and tapioca (Freitas et al., 2004). The cooking method of the yam also plays an important role in determining its GI value. Table 2.1 shows the GI value of yam that is boiled; boiling, followed by cooling, prompts the formation of resistant starches which slows down the digestion rate thus lowering the GI of the yam (Ampofo et al., 2021).

In general, low-GI foods are healthier and recommended for everyone especially those with diabetes so yam would be a good option as a source of carbohydrate. However, in certain cases, high-GI foods are needed; rice and tapioca are good sources of carbohydrates for athletes, especially those doing lots of endurance sports, who need high GI foods to promote rapid glycogen metabolism and to quickly replace the carbohydrates lost during the physical activity (Murray & Rosenbloom, 2018).

The GI, when used in conjunction with in vitro measures of carbohydrate bioavailability, can provide a more comprehensive picture of the real carbohydrate bioavailability of a food ingredient or product (Englyst & Englyst, 2005).

Like a two-sided coin, high GI food have both advantages and disadvantages. Since the high GI food increases the blood sugar content and provides energy immediately, some athletes could have it around strenuous training to replenish the glycogen and provide enough ATP for consumption. Meanwhile, high sugar level could improve cognitive performance and brain activity, as a result, if some people are doing mental work, when they need novel ideas, the supplement of high GI food would be beneficial. However, without the glycogen being consumed, the blood sugar spike it causes might lead to more synthesis of fat, and thus the potential risks of obesity, cardiovascular diseases, and type II diabetes. Instead, the low GI food releases the sugar and increases the blood sugar level at a controllable speed. For people who have more sedentary work or no need for immediate energy, low GI food is preferred. Whether high GI food is beneficial or harmful depends on individual needs.

In terms of sustainability, the total water footprint of corn is 1,222 L/kg, with 947, 81 and 194 litres of green, blue and grey water respectively. The green, blue and grey water for wheat are 1,277, 342 and 207 L/kg, respectively, with the total water consumption is 1,827 L/kg of wheat. Potato has the lowest water footprint among the three products, which is only 287 L/kg. The three contributors are quite low as well: 191, 33 and 63 L/kg (Mekonnen & Hoekstra, 2010). Blue water footprint is the volume of surface and groundwater evaporated as a result of the production of the raw material; green water footprint is the volume of rainwater consumed in the production of the raw material; grey water footprint is the volume of freshwater needed to dilute pollutants, so the water used to produce the raw material meets quality standards (Mekonnen & Hoekstra, 2010).

As for cereals, they generally have a medium water footprint (~1,600 L/kg), however, as shown, maize has a relatively low water footprint among the cereals. The reason why water footprint is different is that different parts of plants are harvested. Potato is the starchy stem of the potato plants, at which all the nutrients are stored, other parts of the plants do not need much energy or water to grow. While the cereals do not have such a structure, only the seeds, the minor part, are harvested and the rest is ditched. Potato has a short harvest time, which is approximately 120 days after planting (Liu et al., 2003). The harvest time for maize varies from 80 days to 120 days (Ashley, 2001). However, it might take 300 days to harvest wheat (HCGA, 2008). That is why cereals have a higher water footprint than potatoes. Yam is the most sustainable crop with only 343 L of water needed to grow 1 kg of it. Rice comes in next at a global average of 2,500 L of water needed to grow 1 kg of it. Tapioca has the highest water footprint of 3,106 L/kg among the three crops because to get the tapioca, the cassava plant needs to undergo some processes; cassava itself has an average water footprint of only 622 L/kg (Mekonnen & Hoekstra, 2010; Situmorang & Manik, 2018). Rice comes in third place and tapioca starch and buckwheat tie for last place with water footprints of over 3,100 L/kg (Mekonnen & Hoekstra, 2010). However, it is worth noting that these water footprint figures are only global averages and the real water footprints of these crops vary based on several factors such as the variety of the crop, the cultivation method used to grow the crop, where the crop is grown, conditions of the environment where the crop is grown, and many more (Yao et al., 2017).

Carbon footprint is a complementary parameter. The carbon emission of potato is 251 Kg CO_2/t harvested (Svubure et al., 2018), and that of cereals are higher, which are 480 Kg CO_2/t and 750 Kg CO_2/t respectively (Zhang et al., 2017). Land use can be used to measure the resource consumed by the crops as well. The yields of potatoes of 90 t/ha are theoretically possible recently (Plant & Food Research, 2013). By contrast, the average yields of corn were 11.8 t/ha in NZ in 2016 (FAR, 2016). The yield of wheat is generally lower than 10 t/ha (FAR, 2010). In a word, potatoes have a very low resource consumption, it shows environmental sustainability, while rice, corn and wheat consume more resources in producing. Yam edible film resulted in higher carbon emissions, likely due to the extensive processing required to obtain such a product (0.88 kg/kg product) (Go, 2009).

2.3.2 Sugar

When it comes to sugar and sweeteners, the amount of research has steadily increased in the past decades, following a 3-step growth. At first, the focus was on non-nutritive synthetic sweeteners, such as aspartame and acesulfame-K, which taste sweet without providing calories (Shankar et al., 2013). Then, the attention moved to non-nutritive sweeteners extracted from plants, such as Stevia and Allulose (Tan et al., 2019). Most recently, nutritive sweeteners (sweet ingredients that deliver calories) have grown in popularity, with products such as agave syrup and date syrup being used more extensively in food manufacturing (Djaoud et al., 2020; Ozuna et al., 2020). The aim of this chapter is carbohydrates for energy, therefore emphasis will be given to nutritive sweeteners, while the non-nutritive counterparts will be included in the discussion due to their high popularity in food formulations.

The past decade was the time of Stevia, when the world became well aware of this new sweetener. What drew attention was two characteristics: extremely high sweetness (150–300 times that of sucrose) and low caloric intake, close to 0 kcal/g (Ashwell, 2015; Wang et al., 2020). Stevia is the commercial name for a pair of glycosides, stevioside and rebaudioside, extracted from the leaves of *Stevia rebaudiana*, a plant found mostly in Brazil and Paraguay (Ashwell, 2015; Wang et al., 2020). Unlike other non-nutritive sweeteners, Stevia does not express strong bitter aftertaste, thanks to its structure and to novel extraction technologies. The water and carbon footprints are about 95% lower than those of sucrose (Ashwell, 2015).

One interesting product is Allulose, a naturally occurring monosaccharide extracted from corn. The market demand for Allulose is booming, with a predicted compound annual growth rate (CAGR) of 14.8% between 2021 and 2027 (Market Watch, 2021b). It is the product of an enzymatic conversion of fructose from corn, delivering sweetness with low calories (0.4 cal/g), which is one-tenth of sucrose that is usually added to make food sweet, and without the loss of upfront sweetness of sucrose, the quality of sweetness or the mouthfeel. However, allulose is three times more expensive than sucrose but still cheaper than the sweetener erythritol. It is important to observe that a successful sweetener must be sweet, cheap and easy to label (Food Navigator USA, 2020b). Being a product of corn, the environmental impact is equal or greater to that of corn (Table 2.4).

Nowadays, syrups are becoming a popular choice as sweeteners: due to the presence of soluble fibers, they provide lower glycemic index than sucrose and higher water binding abilities, making food texture juicier and more pleasant. Agave syrup has grown in popularity over the past 15 years. It is extracted from the leaves of *Agave tequilana* and related plants. The high fructose content allows for its high sweetness (about 1.5 times that of sucrose) at low glycemic index: 11–27 (Espinosa-Andrews et al., 2021; Foster-Powell et al., 2002). The bright yellow appearance resembles that of honey and allows for several applications. When darker colour is needed, date syrup can be a proper choice. This ingredient is new, thus limited research information is available. Sucrose replacement with date syrup in sponge cake resulted in darker, moister product, with sweet, slightly acidic taste (Bhuian et al., 2020). The newest entry is quinoa syrup. Industrial sources present it as mildly sweet, with a delicate bitter aftertaste (Food Navigator, 2021). Quinoa needs low water input (349–877 L water/kg product) (Scanlin & Lewis, 2017) but its processing does result in relevant carbon emissions (1.5 kg CO_2/kg product) (Eco chain, 2020) thus having a mixed environmental impact. Limited geographical availability suggest better impact when used locally rather than upon import.

Another interesting innovation is the result of the upcycling trend. Sweeteners can be extracted from the spent grains, a by-product of the beer industry. The process is simple: applying high temperature, mechanical stress and water, the fibre can be hydrolysed into xylo-olygosaccharides, which are then dried into a powder, without the need for additives (Swart et al., 2021). Their sweetness and caloric value are comparable to those of sucrose, but with lower GI (47) (Kyung et al., 2014) and lower environmental impact (Cimini & Moresi, 2016; Mekonnen & Hoekstra, 2010). Since the raw material is a by-product, it is removed from landfill to be used for food production. Therefore, the carbon footprint of spent grains was calculated to be only 0.02 kg CO_2/kg product (Cimini & Moresi, 2016), lower than that of traditional sweeteners such as sucrose (0.2–0.5 kg CO_2/kg product) (Rein, 2011).

Table 2.4 Innovative food sources of sugar: raw materials, bioavailability (glycemic index) and sustainability (water and carbon footprint)

Products	Raw materials	Bioavailability	Sustainability	
		Glycemic index	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)
Allulose	Corn	No impact	1,222	0.48
		Tan et al. (2019)	Mekonnen and Hoekstra (2010)	Zhang et al. (2017)
Stevia	Stevia (Eupatorium rebaudianum)	No Impact	83	0.14
		Wang et al. (2020)	Ashwell (2015)	Ashwell (2015)
Agave syrup	Agave	11–27	6,549	0.10
		Espinosa-Andrews et al. (2021)	Healabel (2021)	Healabel (2021)
Date syrup	Dates	Not available	2,277	1.1
			Mekonnen and Hoekstra (2010)	Healabel (2021)
Quinoa syrup	Quinoa	Not available	394–877	1.5
			Scanlin and Lewis (2017)	Eco Chain (2020)
Sweeteners from spent grains	Barley malt	54–60	1,950	0.02 (spent grains)
		Kyung et al. (2014)	Mekonnen and Hoekstra (2010)	Cimini and Moresi (2016)

2.4 Conclusions

In closing, energy can be obtained from a wide variety of carbohydrate-based foods. For the majority of the population low glycemic index is preferred, therefore indicating pasta, rolled oats and noodles as good choices. Environmentally, pasta presents the lowest footprint among starch sources and it is highly acceptable, being cheap and neutral in taste. New popular starch-based products are malt flour and boba balls (used in snack food Boba Tea). Traditional sugary foods that have low impact on glycemia and the environment are fruits, followed by syrups when enhanced shelf-life is required. Data seems to indicate that extrusion technologies can lower the glycemic impact of starch-based foods, while fermentation can be a valuable tool to preserve fruit, thus guaranteeing a wholesome source of sugar. Finally, interesting innovations allow for the development of sustainable sweeteners that are either nutritive (xylo-olygosaccharides from brewers spent grains) or non-nutritive (allulose from corn).

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References

Amin, T., Naik, H. R., Hussain, S. Z., Rather, A. H., Murtaza, I., & Dar, B. N. (2017). Structural properties of high-protein, low glycaemic index (GI) rice flour. *International Journal of Food Properties, 20*(11), 2793–2804.

Ampofo, D., Agbenorhevi, J. K., Firempong, C. K., & Adu-Kwarteng, E. (2021). Glycemic index of different varieties of yam as influenced by boiling, frying and roasting. *Food Science and Nutrition, 9*(2), 1106–1111.

Ashley, R. O. (2001). *Corn maturity and ensiling corn.* https://www.ag.ndsu.edu/archive/dickinso/agronomy/cornmaturity.htm. Accessed 20 July 2021.

Ashwell, M. (2015). Stevia, nature's zero-calorie sustainable sweetener: A new player in the fight against obesity. *Nutrition Today, 50*(3), 129.

Atkinson, F. S., Foster-Powell, K., & Brand-Miller, J. C. (2008). International tables of glycemic index and glycemic load values: 2008. *Diabetes Care, 31*(12), 2281–2283.

Bhuian, S. N., Butt, I., Balushi, M. K. A., & Ali, A. (2020). Sensory properties, purchase attributes and usages of date-syrup by expatriate consumers in Oman. *Middle East Journal of Management, 7*(3), 264–281.

Boers, H. M., ten Hoorn, J. S., & Mela, D. J. (2015). A systematic review of the influence of rice characteristics and processing methods on postprandial glycaemic and insulinaemic responses. *The British Journal of Nutrition, 114*(7), 1035–1045.

Cambridge Carbon Footprint. (2013). https://cambridgecarbonfootprint.org/zero-carbon-apple-juice/. Accessed 20 July 2021.

Charles, A. L., Chang, Y. H., Ko, W. C., Sriroth, K., & Huang, T. C. (2005). Influence of amylopectin structure and amylose content on the gelling properties of five cultivars of cassava starches. *Journal of Agricultural and Food Chemistry, 53*(7), 2717–2725.

Chaturvedi, A., Sarojini, G., Nirmala, G., Nirmalamma, N., & Satyanarayana, D. (1997). Glycemic index of grain amaranth, wheat and rice in NIDDM subjects. Plant Foods for Human Nutrition, 50(2), 171–178.

Chaunier, L., Courcoux, P., Della Valle, G. U. Y., & Lourdin, D. (2005). Physical and sensory evaluation of cornflakes crispness. *Journal of Texture Studies, 36*(1), 93–118.

Chiriacò, M. V., Grossi, G., Castaldi, S., & Valentini, R. (2017). The contribution to climate change of the organic versus conventional wheat farming: A case study on the carbon footprint of wholemeal bread production in Italy. *Journal of Cleaner Production, 153*, 309–319.

Chojnicka-Paszun, A., De Jongh, H. H. J., & De Kruif, C. G. (2012). Sensory perception and lubrication properties of milk: Influence of fat content. *International Dairy Journal, 26*(1), 15–22.

Cimini, A., & Moresi, M. (2016). Carbon footprint of a pale lager packed in different formats: Assessment and sensitivity analysis based on transparent data. *Journal of Cleaner Production, 112*, 4196–4213.

Cimini, A., Cibelli, M., Messia, M. C., & Moresi, M. (2019). Commercial short-cut extruded pasta: Cooking quality and carbon footprint vs. water-to-pasta ratio. *Food and Bioproducts Processing, 116*, 150–159.

Cooper, H. R. (1981). *Sensory evaluation of New Zealand commercial whole milk powders: A thesis... for the degree of doctor of philosophy in food technology at Massey University* (Doctoral dissertation). Massey University.

Corollaro, M. L., Endrizzi, I., Bertolini, A., Aprea, E., Demattè, M. L., Costa, F., et al. (2013). Sensory profiling of apple: Methodological aspects, cultivar characterisation and postharvest changes. *Postharvest Biology and Technology, 77*, 111–120.

Countdown. (2021). https://shop.countdown.co.nz/. Accessed 20 July 2021.

Da Costa, J. C., Miki, K. S., da Silva Ramos, A., & Teixeira-Costa, B. E. (2020). Development of biodegradable films based on purple yam starch/chitosan for food application. *Heliyon, 6*(4).

Djaoud, K., Boulekbache-Makhlouf, L., Yahia, M., Mansouri, H., Mansouri, N., Madani, K., & Romero, A. (2020). Dairy dessert processing: Effect of sugar substitution by date syrup and powder on its quality characteristics. *Journal of Food Processing and Preservation, 44*(5), e14414.

Eco Chain. (2020). https://ecochain.com/knowledge/the-environmental-impact-of-quinoa-and-how-we-calculated-it/. Accessed 21 July 2021.

Eleazu, C. O. (2016). The concept of low glycemic index and glycemic load foods as panacea for type 2 diabetes mellitus; prospects, challenges and solutions. *African Health Sciences, 16*(2), 468–479.

Elversson, J., & Millqvist-Fureby, A. (2005). Particle size and density in spray drying—Effects of carbohydrate properties. *Journal of Pharmaceutical Sciences, 94*(9), 2049–2060.

Englyst, K. N., & Englyst, H. N. (2005). Carbohydrate bioavailability. *The British Journal of Nutrition, 94*(1), 1–11.

Espinosa-Andrews, H., Urías-Silva, J. E., & Morales-Hernández, N. (2021). The role of agave fructans in health and food applications: A review. *Trends in Food Science & Technology*.

FAR. (2010). *Cost of production.* https://www.far.org.nz/assets/files/uploads/X90_Cost_of_Production.pdf. Accessed 20 July 2021.

FAR. (2016). *Summary—Survey of maize areas and volumes.* https://www.far.org.nz/assets/files/editable/94fa1fde-5334-429f-b1a1-f34ab5e7ff79.pdf. Accessed 20 July 2021.

Figueiredo, F., Castanheira, É. G., Feliciano, M., Rodrigues, M. Â., Peres, P., Maia, F., Ramos, A., Carneiro, J., Vlad, C., & Freire, F. (2014). Carbon footprint of apple and pear: Orchards, storage and distribution. *Presentation at Energy for Sustainability, 2013*.

Flysjö, A., Thrane, M., & Hermansen, J. E. (2014). Method to assess the carbon footprint at product level in the dairy industry. *International Dairy Journal, 34*(1), 86–92.

Food Composition Data. (2019). *Potato, flesh & skin, waxy, boiled, drained, no salt added (April).* https://www.foodcomposition.co.nz/search/food/X1145/nip. Accessed 20 July 2021.

Food Navigator USA. (2019). https://www.foodnavigator-usa.com/Article/2019/01/22/The-Daily-Crave-on-snacking-trends-We-take-a-longer-term-view. Accessed 20 July 2021.

Food Navigator USA. (2020a). https://www.foodnavigator-usa.com/Article/2020/01/30/Lodaat-Pharma-launches-resistant-potato-starch. Accessed 20 July 2021.

Food Navigator USA. (2020b). https://www.foodnavigator-usa.com/Article/2020/08/26/Sugar-reduction-and-sweetener-trends-From-stevia-and-allulose-to-isomaltulose-not-all-carbohydrates-are-the-same. Accessed 21 July 2021.

Food Navigator USA. (2021). https://www.foodnavigator-usa.com/Product-innovations/Quinoa-syrup-a-refreshing-option-to-rice-syrup. Accessed 21 July 2021.

Foster-Powell, K., Holt, S. H., & Brand-Miller, J. C. (2002). International table of glycemic index and glycemic load values: 2002. *The American Journal of Clinical Nutrition, 76*(1), 5–56.

Freitas, R. A., Paula, R. C., Feitosa, J. P., Rocha, S., & Sierakowski, M. R. (2004). Amylose contents, rheological properties and gelatinization kinetics of yam (*Dioscorea alata*) and cassava (*Manihot utilissima*) starches. *Carbohydrate Polymers, 55*(1), 3–8.

Friedman, M. (2013). Rice brans, rice bran oils, and rice hulls: Composition, food and industrial uses, and bioactivities in humans, animals, and cells. *Journal of Agricultural and Food Chemistry, 61*(45), 10626–10641.

Globe News Wire. (2021, March 17). *The global edible films and coating market was valued at USD 2,659.59 million in 2020, and it is projected to witness a CAGR of 7.64% during the forecast period, 2021–2026.* https://www.globenewswire.com/news-release/2021/03/17/2194598/0/en/The-global-edible-films-and-coating-market-was-valued-at-USD-2-659-59-million-in-2020-and-it-is-projected-to-witness-a-CAGR-of-7-64-during-the-forecast-period-2021-2026.html.

Go. (2009). https://assets.wwf.org.uk/downloads/how_low_report_1.pdf. Accessed 20 July 2021.

Guo, M. Q., Hu, X., Wang, C., & Ai, L. (2017). Polysaccharides: Structure and solubility. *Solubility of Polysaccharides*, 7–21.

Hampton, J., Tang, C., Jayasree Subhash, A., & Serventi, L. (2021). Assessment of pear juice and puree as a fermentation matrix for water kefir. *Journal of Food Processing and Preservation, 45*(3), e15223.

Healabel. (2021). https://healabel.com/c-ingredients/. Accessed 20 July 2021.

Heusala, H., Sinkko, T., Sözer, N., Hytönen, E., Mogensen, L., & Knudsen, M. T. (2020a). Carbon footprint and land use of oat and faba bean protein concentrates using a life cycle assessment approach. *Journal of Cleaner Production, 242*, 118376.

Heusala, H., Sinkko, T., Mogensen, L., & Knudsen, M. T. (2020b). Carbon footprint and land use of food products containing oat protein concentrate. *Journal of Cleaner Production, 276*, 122938.

HGCA. (2008). *The wheat growth guide.* http://www.adlib.ac.uk/resources/000/265/686/WGG_2008.pdf. Accessed 20 July 2021.

Ikeda, K., Arai, R., Fujiwara, J., Asami, Y., & Kreft, I. (2001). Food-scientific characteristics of buckwheat products. In S. S. Ham, Y. S. Choi, N. S. Kim, & C. H. Park (Eds.), *Advances in buckwheat research* (pp. 489–493).

Janse, A. M. (2021, April 24). *Boba shortage could stretch into summer, leave businesses in a bind*. NPR. https://www.npr.org/2021/04/24/990353928/boba-shortage-could-stretch-into-summer-leave-businesses-in-a-bind.

Kaye, Foster-Powell Susanna HA, Holt Janette C, Brand-Miller (2002) International table of glycemic index and glycemic load values: 2002. The American Journal of Clinical Nutrition 76(1) 5-56 10.1093/ajcn/76.1.5.

Kim, E. H. J., Petrie, J. R., Motoi, L., Morgenstern, M. P., Sutton, K. H., Mishra, S., & Simmons, L. D. (2008). Effect of structural and physicochemical characteristics of the protein matrix in pasta on in vitro starch digestibility. *Food Biophysics, 3*(2), 229–234.

Kyung, M., Choe, H., Jung, S., Lee, K., Jo, S., Seo, S., ... & Kim, Y. (2014). Effects of xylooligosaccharide-sugar mixture on glycemic index (GI) and blood glucose response in healthy adults. Journal of Nutrition and Health, 47(4), 229-235.

Li, C., You, Y., Chen, D., Gu, Z., Zhang, Y., Holler, T. P., Ban, X., Hong, Y., Cheng, L., & Li, Z. (2021). A systematic review of rice noodles: Raw material, processing method and quality improvement. *Trends in Food Science & Technology, 107*, 389–400.

Liu, Q., Weber, E., Currie, V., & Yada, R. (2003). Physicochemical properties of starches during potato growth. *Carbohydrate Polymers, 51*(2), 213–221.

Low, Y. K., Effarizah, M. E., & Cheng, L. H. (2020). Factors influencing rice noodles qualities. *Food Reviews International, 36*(8), 781–794.

Market Watch. (2021a, April 19). *Global bubble tea market 2021–2025 with top countries data industry trends, share, size, demand, growth opportunities, industry revenue, future and business analysis by forecast.* https://www.marketwatch.com/press-release/global-bubble-tea-market-2021-2025-with-top-countries-data-industry-trends-share-size-demand-growth-opportunities-industry-revenue-future-and-business-analysis-by-forecast-2021-04-19. Accessed 20 July 2021.

Market Watch. (2021b, June 24). *Global bubble tea market 2021–2025 with top countries data industry trends, share, size, demand, growth opportunities, industry revenue, future and business analysis by forecast.* https://www.marketwatch.com/press-release/allulose-cas-551-68-8-market-opportunity-cagr-of-148-emerging-markets-offer-lucrative-growth-opportunities-with-top-regions-and-top-countries-data-forecast-to-2026-2021-06-24. Accessed 20 July 2021.

Mekonnen, M., & Hoekstra, A. (2010). *The green, blue and grey water footprint of crops and derived crop productss, value of water research report series No. 47.* https://www.waterfootprint.org/media/downloads/Report47-WaterFootprintCrops-Vol1.pdf

Mekonnen, M. M., & Hoekstra, A. Y. (2012). A global assessment of the water footprint of farm animal products. *Ecosystems, 15* (3), 401-415.

Min, J. E., Green, D. B., & Kim, L. (2017). Calories and sugars in boba milk tea: Implications for obesity risk in Asian Pacific Islanders. *Food Science & Nutrition, 5*(1), 38–45.

Murray, B., & Rosenbloom, C. (2018). Fundamentals of glycogen metabolism for coaches and athletes. *Nutrition Reviews, 76*(4), 243–259.

Nagendra, P. M., Sanjay, K. R., Shravya, K. M., Vismaya, M. N., & Nanjunda, S. S. (2011). Health benefits of rice bran—A review. *Journal of Nutrition & Food Sciences, 1*(3), 1–7.

New World. (2021). https://www.newworld.co.nz/discover/online-shopping. Accessed 20 July 2021.

NIH. (2021). *National Institute of Aging*. https://www.nia.nih.gov/health/important-nutrients-know-proteins-carbohydrates-and-fats. Accessed 20 July 2021.

Nnadi, I. M., & Keshinro, O. O. (2016). The effect of the glycaemic response of three commonly consumed meals on postprandial plasma glucose in type 2 diabetics at the University of Nigeria Teaching Hospital, Enugu. *South African Journal of Clinical Nutrition, 29*(2), 90–94.

Okayasuand, H., & Naito, S. (2001). Sensory characteristics of apple juice evaluated by consumer and trained panels. *Journal of Food Science, 66*(7), 1025–1029.

Orlandi, R. D. M., Verruma-Bernardi, M. R., Sartorio, S. D., & Borges, M. M. R. (2017). Physicochemical and sensory quality of brown sugar: Variables of processing study. *Journal of Agricultural Science, 9*(2), 115–121.

Ozuna, C., Trueba-Vázquez, E., Moraga, G., Llorca, E., & Hernando, I. (2020). Agave syrup as an alternative to sucrose in muffins: Impacts on rheological, microstructural, physical, and sensorial properties. *Food, 9*(7), 895.

Pinto, V. R., Dias, A. C. C., de Assis, F. S., Barbosa, L. C., dos Santos, P. C., Alves, J. J. S., et al. (2021). The effect of different types of sugars on the physicochemical characteristics, sensory acceptance, and bioactive compounds of Jaboticaba Jellies. *Journal of Culinary Science & Technology*, 1–18.

Pi-Sunyer, F. X. (2002). Glycemic index and disease. *The American Journal of Clinical Nutrition, 76*(1), 290S–298S.

Plant & Food Research. (2013). *Maximising potato yield.* https://potatoesnz.co.nz/mdocs-posts/maximising-potato-yield-in-canterbury-s-sinton/?mdocs-file=6442&mdocs-url=false. Accessed 20 July 2021.

PR Distribution. (2021, February 13). *Japan's Fermented Superfood "Nuka" Rice Bran in a Tube Arrives in the US*. https://www.prdistribution.com/news/japan-s-fermented-superfood-nuka-rice-bran-in-a-tube-arrives-in-the-us.html

Ridoutt, B. G., Williams, S. R. O., Baud, S., Fraval, S., & Marks, N. (2010). Short communication: The water footprint of dairy products: Case study involving skim milk powder. Journal of Dairy Science 93(11) 5114–5117 S0022030210005527 10.3168/jds.2010-3546.

Rein, P. (2011). Sustainable production of raw and refined cane sugar. 1 Paper presented to SIT Conference.

Robertson, T. M., Alzaabi, A. Z., Robertson, M. D., & Fielding, B. A. (2018). Starchy carbohydrates in a healthy diet: The role of the humble potato. *Nutrients, 10*(11), 1764.

Ruini, L., Marchelli, L., & Filareto, A. (2013). LCA methodology from analysis to actions: examples of barilla's improvement projects. In *The 6th international conference on lifecycle management in gothenburg 2013*.

Scanlin, L., & Lewis, K. A. (2017). Quinoa as a sustainable protein source: Production, nutrition, and processing. In *Sustainable protein sources* (pp. 223–238). Academic.

Scazzina, F., Dall'Asta, M., Casiraghi, M. C., Sieri, S., Del Rio, D., Pellegrini, N., & Brighenti, F. (2016). Glycemic index and glycemic load of commercial Italian foods. *Nutrition, Metabolism and Cardiovascular Diseases, 26*(5), 419–429.

Shankar, P., Ahuja, S., & Sriram, K. (2013). Non-nutritive sweeteners: Review and update. *Nutrition, 29*(11–12), 1293–1299.

Shevkani, K., Singh, N., Bajaj, R., & Kaur, A. (2017). Wheat starch production, structure, functionality and applications—A review. *International Journal of Food Science and Technology, 52*, 38–58.

Sissons, M. (2008). Role of durum wheat composition on the quality of pasta and bread. *Food, 2*(2), 75–90.

Situmorang, A., & Manik, Y. (2018). Initial sustainability assessment of tapioca starch production system in Lake Toba area. *IOP Conference Series: Materials Science and Engineering, 337*, 1–7.

Smith, H. A., Gonzalez, J. T., Thompson, D., & Betts, J. A. (2017). Dietary carbohydrates, components of energy balance, and associated health outcomes. *Nutrition Reviews, 75*(10), 783–797.

Starowicz, M., Koutsidis, G., & Zieliński, H. (2018). Sensory analysis and aroma compounds of buckwheat containing products—A review. *Critical Reviews in Food Science and Nutrition, 58*(11), 1767–1779.

Sugiyama, M., Tang, A. C., Wakaki, Y., & Koyama, W. (2003). Glycemic index of single and mixed meal foods among common Japanese foods with white rice as a reference food. *European Journal of Clinical Nutrition, 57*(6), 743–752.

Svubure, O., Struik, P., Haverkort, A., & Steyn, J. (2018). Carbon footprinting of potato (*Solanum tuberosum L.*) production systems in Zimbabwe. *Outlook on Agriculture, 47*(1), 3–10.

Swart, L. J., Bedzo, O. K., van Rensburg, E., & Görgens, J. F. (2021). Intensification of Xylo-oligosaccharides production by hydrothermal treatment of Brewer's spent grains: The use of extremely Low acid catalyst for reduction of degradation products associated with high solid loading. *Applied Biochemistry and Biotechnology, 193*(6), 1979–2003.

Tan, V. W. K., Wee, M. S. M., Tomic, O., & Forde, C. G. (2019). Temporal sweetness and side tastes profiles of 16 sweeteners using temporal check-all-that-apply (TCATA). *Food Research International, 121*, 39–47.

USDA. (1989, October 1). *Noodles, japanese, soba, dry*. https://fdc.nal.usda.gov/fdc-app.html#/food-details/168906/nutrients

USDA, (2019). Milk, whole, 3.25% milkfat, with added vitamin D. https://fdc.nal.usda.gov/fdc-app.html#/fooddetails/746782/nutrients

USDA. (2013a, May 1). *Rice noodles, cooked*. https://fdc.nal.usda.gov/fdc-app.html#/food-details/168914/nutrients

USDA. (2013b, May 1). *Rice noodles, dry*. https://fdc.nal.usda.gov/fdc-app.html#/food-details/169742/nutrients

USDA. (2015, May 1). *Pasta, whole-wheat, cooked (Includes foods for USDA's Food Distribution Program)*. https://fdc.nal.usda.gov/fdc-app.html#/food-details/168910/nutrients

USDA. (2020). *FoodData Central*. https://fdc.nal.usda.gov/fdc-app.html#/food-details/753438/nutrients. Accessed 20 July 2021.

USDA. (2021). *How many calories are in one gram of fat, carbohydrate, or protein?* https://www.nal.usda.gov/fnic/how-many-calories-are-one-gram-fat-carbohydrate-or-protein. Accessed 20 July 2021.

Usubharatana, P., & Phungrassami, H. (2015). Carbon footprint of cassava starch production in north-eastern Thailand. *Procedia CIRP, 29*, 462–467.

Vernaza, M. G., Biasutti, E., Schmiele, M., Jaekel, L. Z., Bannwart, A., & Chang, Y. K. (2012). Effect of supplementation of wheat flour with resistant starch and monoglycerides in pasta dried at high temperatures. International journal of food science & technology, 47(6), 1302–1312.

Wang, J., Zhao, H., Wang, Y., Lau, H., Zhou, W., Chen, C., & Tan, S. (2020). A review of stevia as a potential healthcare product: Up-to-date functional characteristics, administrative standards and engineering techniques. *Trends in Food Science & Technology.*

Wee, M. S., & Henry, C. J. (2020). Reducing the glycemic impact of carbohydrates on foods and meals: Strategies for the food industry and consumers with special focus on Asia. *Comprehensive Reviews in Food Science and Food Safety, 19*(2), 670–702.

Willett, W., Manson, J., & Liu, S. (2002). Glycemic index, glycemic load, and risk of type 2 diabetes. *The American Journal of Clinical Nutrition, 76*(1), 274S–280S. https://doi.org/10.1111/j.1365-2621.2012.02974.x.

Wronkowska, M., & Haros, M. (2014). Wet-milling of buckwheat with hull and dehulled—The properties of the obtained starch fraction. *Journal of Cereal Science, 60*(3), 477–483.

Xu, X., Zhang, B., Liu, Y., Xue, Y., & Di, B. (2013). Carbon footprints of rice production in five typical rice districts in China. *Acta Ecologica Sinica, 33*(4), 227–232.

Xu, Z., Xu, W., Zhang, Z., Yang, Q., & Meng, F. (2017). Measurement and evaluation of carbon emission for different types of carbohydrate-rich foods in China. *Chemical Engineering Transactions, 61*, 409–414.

Xu, Z., Fu, Z., Zhai, Z., Yang, X., Meng, F., Feng, X., et al. (2020). Comparative evaluation of carbon footprints between rice and potato food considering the characteristic of Chinese diet. *Journal of Cleaner Production, 257*, 120463.

Yang, Y. X., Wang, H. W., Cui, H. M., Wang, Y., Yu, L. D., Xiang, S. X., & Zhou, S. Y. (2006). Glycemic index of cereals and tubers produced in China. *World Journal of Gastroenterology, 12*(21), 3430–3433.

Yao, Z., Zheng, X., Liu, C., Lin, S., Zuo, Q., & Butterbach-Bahl, K. (2017). Improving rice production sustainability by reducing water demand and greenhouse gas emissions with biodegradable films. *Scientific Reports, 7*(39855).

Zhang, D., Shen, J., & Zhang, F. (2017). Carbon footprint of grain production in China. *Scientific Reports, 7*, 4126.

Zi, Y., Ding, J., Song, J., Peng, Y., Li, C., Zhu, X., Guo, W., & Humphreys, G. (2018). Grain yield, starch content and activities of key enzymes of waxy and non-waxy wheat (*Triticum aestivum* L.). *Scientific Reports, 8*, 4548.

3 Carbohydrates for Fibre

Sophie Carr Paterson, Toni Christina Mulholland, Annu Mehta, and Luca Serventi

Abstract

Fibre is extremely important in human diet. Not for energy, but in support of our health. It helps preventing cardiovascular disease and colorectal cancer by reducing the absorption rate of glucose and cholesterol. In addition, fibre comes with a load of antioxidants, minerals and vitamins. Fibre can be soluble or insoluble in water, resulting in different effects on health and food quality. Sources are plant-based: mushrooms, fruits, seeds, vegetables and wholegrains. Their environmental impact is very low, especially for produce, which mostly offers soluble fibre from fruits and vegetables. Grains and seeds (mostly sources of insoluble fibre) can be more demanding, thus upcycled sources of fibre (defatted seeds, okara) are an excellent innovation. Inulin, mucilage-rich seeds and mushrooms are now extremely popular due to health properties, low footprint and enhanced food quality (juicy texture).

Keywords

Footprint · Insoluble fibre · Mushrooms · Prebiotics · Soluble fibre · Upcycling

3.1 Fibre: Soluble and Insoluble

Dietary fibre is a critical component of the human diet. It has the unique ability to deliver several health benefits, despite the fact that it does not provide any energy. This is due to the fact that fibre cannot be digested by humans. Nonetheless, it is crucial to a healthy diet. Dietary fibre is found in plant-based foods such as grains, seeds, fruit and vegetables (Dhingra et al., 2012). Chemically, numerous classifications are available, based on the molecular structure. Nutritionally, fibre is classified based on its water solubility into soluble fibre and insoluble fibre (Dhingra et al., 2012; Gidley & Yakubov, 2019). Common examples of soluble fibre are, in increasing order of molecular length, oligosaccharides, β-glucans, inulin, gums, pectin and resistant starch. Examples of insoluble fibre are hemicellulose, cellulose, lignin and chitin (Gidley & Yakubov, 2019; Kalač, 2009; Mudgil, 2017). Chitin is a nitrogen-containing polysaccharide found in shellfish (lobster, shrimps), mushrooms and insects. The shell of fish is not typically eaten, and insects' consumption has not reached worldwide levels, thus making mushrooms the

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Fig. 3.1 Representative sources of soluble fibre: traditional (banana) and innovative (mushroom used to make jerky)

major source of chitin in human diet (Kalač, 2009).

Dietary fibre exerts numerous nutritional benefits. For starter, soluble fibre absorbs large volumes of water in the intestine, thus reducing the rate of absorption of glucose (Evans, 2020; Tamargo et al., 2020) and cholesterol (Tamargo et al., 2020). In addition, fibre reduces appetite, constipation, risk of cardiovascular disease and risk of colorectal cancer (Dhingra et al., 2012). Not less relevant, fibre often carries a load of nutrients such as antioxidants, minerals and vitamins, providing further benefits to the consumers (Das et al., 2020). Furthermore, soluble fibre can be digested by beneficial microorganisms in the human intestine, thus supporting gut health. This is possible due to the microbial production of bioactives (upon digestion of soluble fibre) and consequent inhibition of pathogenic microorganisms (Parnell & Reimer, 2012). Insoluble fibre acts mostly as a bulking agent, resisting degradation and providing means for excretion of indigested material (Mudgil, 2017).

Due to its structure, fibre affects food quality in terms of texture and, consequently, taste. Most people might think of fibre-rich foods as chalky and unpleasant, that is the effect of high amounts of insoluble cell wall material. Nonetheless, nutty aroma and flavour can positively affect food quality. Soluble fibre typically provides thick, slimy, juicy texture that may be beneficial depending on the food application (Chakraborty et al., 2019; Torbica et al., 2019). The physical role of dietary fibre is due to its ability to bind water, gel, thicken (soluble fibre) and provide bulk (insoluble fibre) (Gidley & Yakubov, 2019).

Therefore, dietary fibre is a crucial nutrient that can benefit human health and food quality. Sources are numerous, as are the concentrations, environmental impacts and effects on sensory quality. This chapter discuss representative sources of soluble and insoluble fibre, explaining their content, quality, water and carbon footprint, as well as consumer acceptability. First, traditional sources will be presented. Later, innovative sources will be discussed. Innovation is considered either as a new food product or as an existing food product with high success: compound annual growth rate (CAGR) above 5%. An example of the modern trajectory of fibre-rich food products is depicted in Fig. 3.1.

3.2 Traditional Food Sources of Fibre

3.2.1 Soluble

Traditionally, soluble fibre can be obtained from a myriad of foods and food products of the plant kingdom. Fruits, vegetables, legumes, cereals, mucilaginous seeds and fungi are the key contributors. Among all these, representative case studies are discussed in Table 3.1: bananas, dry dates and apples (produce), flaxseeds (mucilaginous seeds), red kidney beans (legumes), rolled oats (cereals), mushrooms (fungi) and carrots (vegetables).

Quantity-wise, bananas offer the largest amount of soluble fibre, in the form of resistant starch. Values range from 16 to 42 g/100 g based on the cultivar and on the degree of ripening: the more ripened the less resistant starch (replaced by sugar) (Li et al., 2020). High levels are also found in dry dates (6.0–16 g/100 g of oligosaccharides) and flaxseeds (12–15 g/100 g of mucilage containing Arabynoxylans and Rhamnose polysaccharides (Kajla et al., 2015; Kamal-Eldin et al., 2020). In the case of dates, the dry form allows for higher content than in apples (6.4–8.8 g/100 g of pectin, based on cultivar) (Suni et al., 2000). Whereas for flaxseeds it is the mucilage released upon soaking in water that contributes to the soluble fibre intake. Oligosaccharides are also found in commonly eaten legumes such as red kidney beans (9.0–15 g/100 g) (Kan et al., 2017). A staple breakfast food such as rolled oats contributes to 2.3–8.5 g/100 g of soluble β-glucans, higher than the 1.1–3.5 g/100 g of the same nutrient delivered by mushrooms (Mirończuk-Chodakowska & Witkowska, 2020; Rasane et al., 2015). Each type of soluble fibre (resistant starch, oligosaccharides, polysaccharides, pectin and β-glucans) expresses different mechanisms (Dhingra et al., 2012) and they should all be included in a healthy diet to lower the risk of cardiovascular diseases and support intestinal health.

Environmentally, the impact of these plant-based foods is low, with little water required and minimal carbon produced by most of these foods, with a few exceptions (Table 3.1). Dry dates require large volume of water (1,250 L water/kg product) due mainly due to their cultivation and the drying process (Mekonnen & Hoekstra, 2011). Flaxseeds require very large volumes of water (5,168 L water/kg product) to be grown and harvested in large quantity (Ziolkovska, 2012) therefore limiting its applications. Finally, cereals like oats require moderate water quantity (2,416 L water/kg product) to be harvested and produced into rolled oats (Rasane et al., 2015). In terms of emissions, all these foods produce minimal pollution, with carbon footprint ranging from 0.10 to 2.0 kg CO_2/kg product for apples and red kidney beans, respectively (Figueiredo et al., 2014; Greeneatz, 2021). Fruits, vegetables and mushrooms seem to offer the lowest environmental impact. This data is based on local and seasonal production. Therefore, it is important to recommend the consumption of locally grown and seasonal produce.

Consumer acceptance depicts a similar scenario, where most of these foods are affordable: 0.17–0.53 NZD/100 g for carrots and bananas, respectively (Countdown, 2021). Higher prices are charged for dry dates, flaxseeds, oats and mushrooms. Again, local and seasonal choices will lower the price, thus allowing more people to access these foods. Big variables to consider are variations in oil prices and climate which greatly impacts food prices, possibly excluding some consumers from healthy food choices (Taghizadeh-Hesary et al., 2019; Wossen et al., 2018). Therefore, a multi-step process should be adopted to guarantee food security, combining government policies with enhanced irrigation technology (Wossen et al., 2018). Sensory-wise, each category offers a different experience: fruits offer sweetness and a variety of soft and crunchy texture (Bugaud et al., 2011; Seppä et al., 2012; Singh et al., 2015) while vegetables may provide sweetness in the case of carrots, as well as firm,

Table 3.1 Representative food sources of soluble fibre: products, nutritional value (quantity, quality), sustainability (water and carbon footprint) and consumer acceptability (price, sensory)

	Nutrition		Sustainability		Acceptability	
Food products	Fibre quantity (g/100 g)	Fibre quality (profile)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory profile
Bananas	16–42	Resistant starch	330	0.25–1.28	0.25–0.53	Firm, sweet, mealy, banana flavour
	Li et al. (2020)	Li et al. (2020)	Roibás et al. (2015)	Roibás et al. (2015), Svanes and Aronsson (2013)	Countdown (2021)	Bugaud et al. (2011)
Dates, dried	6.0–16	Oligosaccharides	1,250	1.10	0.48	Sweet, chewy, caramelised
	Kamal-Eldin et al. (2020)	Kamal-Eldin et al. (2020)	Mekonnen and Hoekstra (2011)	Healabel (2021)	Countdown (2021)	Singh et al. (2015)
Flaxseeds	12–15	Arabinoxylans, Rhamnose polysaccharides	5,168	0.46	0.80	Brown, elastic, moist (when added to noodles)
	Kajla et al. (2015)	Ziolkovska (2012)	Mekonnen and Hoekstra (2011)	Jaiswal and Agrawal (2020)	Countdown (2021)	Zhu and Li (2019)
Red kidney beans	9.0–15	Oligosaccharides	456	2.0	0.26	Beany, earthy, smoky
	Kan et al. (2017)	Kan et al. (2017)	Hoekstra (2014)	Greeneatz (2021)	Countdown (2021)	Mishra et al. (2017)
Apples	6.4–8.8	Pectin	822	0.10	0.42	Sweet, juicy, crisp
	Suni et al. (2000)	Licht et al. (2010)	Mekonnen and Hoekstra (2011)	Figueiredo et al. (2014)	Countdown (2021)	Seppä et al. (2012)
Rolled oats	2.3–8.5	β-glucans	2,416	0.55	0.47	Dry, chewy
	Rasane et al. (2015)	Rasane et al. (2015)	Mekonnen and Hoekstra (2011)	Heusala et al. (2020)	Countdown (2021)	Hu et al. (2014)
Mushrooms	1.1–3.5	β-glucans	14–18	0.6–0.7	2.0–6.0	Earthy/humus, woody, nutty, brown, umami, aromatics
	Mirończukska-Chodakow and Witkowska (2020)	Chodakowska-Mirończuk and Witkowska (2020)	Hoekstra et al. (2011)	Hoekstra et al. (2011)	Countdown (2021)	Chun et al. (2020)
Carrots	1.7–1.8	Polysaccharides of uronic acid, arabinose and galactose	329	0.1–0.3	0.17–0.30	Orange, firm, juicy, carrot flavour, sweet
	Svanberg et al. (1997)	Nyman et al. (1993)	Hossain et al. (2021)	Röös and Karlsson (2013)	Countdown (2021)	Bongoni et al. (2014)

juicy texture and characteristic flavour (Bongoni et al., 2014). Grains and seeds offer dark colour, harder texture, with either cereal- or beany-flavour (Hu et al., 2014; Mishra et al., 2017; Zhu and Li, 2019). Interestingly, mushrooms provide the umami flavour typical of animal-based foods such as meat and dairy (Chun et al., 2020). Umami is a Japanese word used to describe one of the five basic tastes. It is savoury and meaty and it is chemically associated to the presence of the compound monosodium glutamate, famously known as MSG (Sun et al., 2020). This peculiar property of mushrooms is extremely handy as you will see in the new food products developed (Sects. 3.3.1 and 3.3.2).

3.2.2 Insoluble

Insoluble fibre is the brush that cleans up our intestine and blood vessels. We need it and, luckily, numerous sources are available. In fact, most plant foods contain more fibre in the insoluble form rather than in the soluble one, as it can be seen in Tables 3.1 and 3.2. Legumes, cereals, rye bread, fungi and seeds are excellent sources of insoluble fibre, as well as defatted nuts (coconut flour).

Most seeds and nuts contain high levels of fat and fibre. Therefore, defatted meals represent an excellent source of fibre. For example, coconut flour delivers 11–46 g/100 g of insoluble fibre, in the form of cellulose, hemicellulose and lignin (Adeloye et al., 2020), making it one of the most abundant sources of insoluble fibre. The second best source of insoluble fibre is legumes such as red kidney beans, followed by mushrooms: 26–34 and 19–23 g/100 g, respectively (Figueiredo et al., 2014; Kan et al., 2017). Rye bread, rolled oats and flaxseeds offer lower values: 3.8–8.5 g/100 g (Dhingra et al., 2012; Kajla et al., 2015; Sibakov et al., 2013). While cellulose, hemicellulose and lignin sources are abundant, less options are available for arabynoxylans, which require wholegrain foods such as dark rye bread or whole flours, thus raising the importance of consuming wholefoods rather than refined. In addition, wholegrains provide satiety and deliver vitamins, minerals and antioxidants (Andersson et al., 2010). Finally, another type of insoluble fibre, chitin, can be obtained from mushrooms in large quantity (1.9–2.3 g/100 g fresh weight), providing protection against cardiovascular diseases, allergies and infections (Dong et al., 2019).

Environmentally, mushrooms and coconut flour are the best choices. Mushrooms growing is extremely efficient, requiring only 14–18 L water/kg product and producing as little as 0.6–0.7 kg CO_2/kg product (Hoekstra et al., 2011). Coconut flour refers to the food product that is obtained after drying, expelling and extracting most of the oil/milk from coconut meat. This is then grinded and pulverized into meal and used as a wheat substitute. This process requires little use of natural resources (834 L water/kg product) (Mekonnen & Hoekstra, 2011) and is less demanding in terms of water usage in comparison to flaxseeds with a water footprint of 2,687 L water/kg product. Plus, the carbon footprint is low (0.1–0.4 kg CO_2/kg product) being a by-product of coconut processing. Although, in general, the environmental impact of harvesting coconut is quite low, coastal mangroves containing ecosystems are being cleared for coconut monocrops which negatively impacts biodiversity and depletes the soil (Castillo et al., 2018).

Unfortunately, coconut flour and mushrooms can be expensive, possibly shifting consumer choices toward cheaper options such as legumes (0.26 NZD/100 g of red kidney beans), dark rye bread and rolled oats (0.47 NZD/100 g) (Countdown, 2021). Taste-wise, coconut flour has a cream colour and its texture is very dry (Chandrashekar et al., 2019). It has a nutty odour and is less of a coconut flavour and more of a bland taste due to the reduced fat content. It is also bulkier than usual flour and takes up more space per unit volume. The use of coconut flour in bread showed an improvement in sensory profile with bulk density decreasing and water and oil absorption capacity of the blend increasing (Adeloye et al., 2020). In comparison to other beans, red kidney beans have a darker, more crimson shade with a mildly beany flavour, and can hold shape well (Mishra et al., 2017). Red kidney beans are commonly used in dishes such

Table 3.2 Representative food sources of insoluble fibre: products, nutritional value (quantity, quality), sustainability (water and carbon footprint) and consumer acceptability (price, sensory)

	Nutrition		Sustainability		Acceptability	
Food products	Fibre quantity (g/100 g)	Fibre quality (profile)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory profile
Coconut flour (oilcake)	11–46	Cellulose, hemicellulose, lignin	834	0.1–0.4	0.87	Light, compact, hard, dry
	Adeloye et al. (2020)	Adeloye et al. (2020)	Mekonnen and Hoekstra (2011)	Sampaio et al. (2021)	Countdown (2021)	Chandrashekar et al. (2019)
Red kidney beans	26–34	Cellulose, lignin	456	2.0	0.26	Dark, mildly beany, hold texture
	Kan et al. (2017)	Kan et al. (2017)	Hoekstra (2014)	Greeneatz (2021)	Countdown (2021)	Hoekstra (2014)
Dark Rye bread	8.5	Arabynoxylans	1,544	0.73	0.47	Dark, intense aroma and flavour (acid, earthy, salty), dense
	Sibakov et al. (2013)	Sibakov et al. (2013)	Mekonnen and Hoekstra (2011)	Jensen and Arlbjørn (2014)	Countdown (2021)	Zieliński et al. (2008)
Rolled oats	6.5	Cellulose, lignin	2,416	0.55	0.47	Dry, chewy
	Dhingra et al. (2012)	Dhingra et al. (2012)	Mekonnen and Hoekstra (2011)	Heusala et al. (2020)	Countdown (2021)	Hu et al. (2014)
Flaxseeds	3.8	Cellulose, lignin	5,168	0.46	0.80	Brown, elastic, moist (when added to noodles)
	Kajla et al. (2015)	Ziolkovska (2012)	Mekonnen and Hoekstra (2011)	Jaiswal and Agrawal (2020)	Countdown (2021)	Zhu and Li (2019)
Mushrooms	1.9–2.3	Chitin	14–18	0.6–0.7	2.0–6.0	Earthy/humus, woody, nutty, brown, green, umami, aromatics
	Figueiredo et al. (2014)	Figueiredo et al. (2014)	Hoekstra et al. (2011)	Hoekstra et al. (2011)	Countdown (2021)	Chun et al. (2020)

as chilli and bean salads, rarely consumed an individual product as the overall sensory profile is not enticing. Dark rye bread tastes earthy, salty, acid (sourdough) and has a dark brown colour (Zieliński et al., 2008). Most wholegrain foods share similar responses, thus limiting their consumer acceptability (Fig. 3.2).

3.3 Innovative Food Sources of Fibre

3.3.1 Soluble

Innovative food products and popular traditional products both offer solutions to those seeking soluble fibre and are summarised in Table 3.3.

For example, inulin powder, a common vegetable extract, has seen a surge in interest, with a predictive CAGR of 10.9% in the 2020–2025 period, with a massive 2.03 billion US dollars of global value to be reached (GlobeNewswire, 2019). Inulin is a polysaccharides made of fructan units. It is primarily found in chicory root, garlic, onion, Jerusalem artichoke and other vegetables (Nwafor et al., 2017). It has been known as prebiotic fibre, antioxidant, aid in the prevention of cardiovascular disease and others benefits (Wan et al., 2020). It is recently been used as prebiotic as well as texture improvers, fat replacer, producing juicy mouthfeel and viscous food solutions, with applications ranging from beverages, bakery, dairy and confectionery (Sayed & Khalil, 2017; Sensus, 2021; Wan et al., 2020). The environmental impact depends on the raw material. In the case of chicory root, the most abundant source of inulin, very limited amount of water is needed (50–200 L water/kg product) (Atzori et al., 2019) and even less carbon is emitted (0.4 kg CO_2/kg product) (Healabel, 2021) thus making this ingredient sustainable. The price is high (2.4 NZD/100 g) but the amount needed is minimal, in the order of 0.1–1% for most applications (Sayed & Khalil, 2017).

Quinoa syrup is the most recent innovation in this field, having entered the market only in 2021 (Faravelli, 2021). Its fibre content reaches 56 g/100 g of soluble fibre (arabinans and homogalacturonans) (Graf et al., 2015; Faravelli, 2021). Quinoa is considered a drought-tolerant crop and receives less than 150 mm of annual rainfall in the main production zones. The water requirements for quinoa are between 254 and 381 mm with combined irrigation and precipitation (Scanlin & Lewis, 2017). The water footprint required to produce a gram of protein as determined by Mekonnen and Hoekstra 2011) which is L water/g protein, is 31 L for milk, 21 L for cereal grains and 112 L for bovine meat. Taking into consideration the water requirements for quinoa yield 2–3 t/ha which would provide 268–401 kg of protein/ha, the water footprint of quinoa falls between 6.3 and 14.2 L/g of protein (Scanlin & Lewis, 2017). Quinoa production is still small, with various industrial-scale innovations being introduced in the harvesting and post-harvest stages to replace traditional practises that were initially designed for small-scale production. The current 'inefficiencies' in the post-harvest cycle of quinoa are related to machinery that needs to be more dynamic and economical to meet the growing demand of consumers (Angeli et al., 2020). There is not a high volume of waste water associated with the processing of quinoa, however it is worthy to note that it is most commonly purchased raw and left for consumers to dispose of their wastewater post cooking. The carbon footprint might present minor concerns: 1.03 kg CO_2/kg quinoa (Vázquez-Rowe et al., 2017), which would further increase when considering processing into a syrup (data not available).

A product that attracts the attention is undoubtedly mushroom jerky (Primal, 2021). This product is sold in strips, resembling the sensory experience of beef jerky. Mushrooms, in this case shiitake mushrooms, are a great fit for this application due to their content of MSG (delivering umami flavour), chitin (providing structure to the strips) and β-glucans (providing juiciness) (Geetha et al., 2021). Wheat gluten is added for structure and flavours (soy sauce, chilli) are used to optimize the taste (Primal, 2021). The environmental impact is minimal, as shown in Sect. 3.2.2. Mushroom jerky has great potential: nutrition, taste, sustainability. Only one aspect is challenging: price. Typically, a 28 gram strip of mushroom jerky costs 3.50 NZD, meaning 12.5 NZD/100 g (TheMarket NZ, 2021). If cheaper technologies were to be developed, mushroom jerky could be an excellent source of soluble fibre, as well as insoluble fibre, protein and other bioactives.

Oat yogurt is another way to get β-glucans: 0.4 g/100 g (Oatly, 2021; Rasan et al., 2015). It mimics the taste and texture of normal yoghurt, maintaining a "similar creamy consistency" to dairy based counter-parts (Sethi et al., 2016). Interestingly, the creamier texture of vegan yoghurt was attributed to starch and to soluble fibre (namely β-glucans) which provides viscosity and mouthfeel, in addition to nutritional benefit (Brückner-Gühmann et al., 2019). Swedish

Fig. 3.2 Representative sources of insoluble fibre: traditional (red kidney beans, coconut flour) and innovative (defatted sunflower meal)

Table 3.3 Innovative food sources of soluble fibre: raw materials, bioavailability (fibre profile) and sustainability (water and carbon footprint)

Products	Raw materials	Bioavailability	Sustainability	
		Soluble fibre profile	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)
Inulin powder	Chicory root	90 g/100 g Fructan polysaccharides	50–200	0.4
		Nwafor et al. (2017), Sayed and Khalil (2017), Sensus (2021), Wan et al. (2020)	Atzori et al. (2019)	Healabel (2021)
Quinoa syrup	Quinoa	56 g/100 g Arabinans, Homogalacturonans	254–381	1.03
		Faravelli (2021), Graf et al. (2015)	Scanlin and Lewis (2017)	Vázquez-Rowe et al. (2017)
Mushroom jerky	Mushrooms	1.2 g/100 g β-glucans	14–18	0.6–0.7
		Geetha et al. (2021), Primal (2021)	Hoekstra et al. (2011)	Hoekstra et al. (2011)
Oat yogurt	Oats	0.4 g/100 g β-glucans	2,536	0.55
		Oatly (2021), Rasane (2015)	Hoekstra (2019)	Heusala et al. (2020)

plant-based company Oatly is the first company to launch oat yoghurt in the market in the UK, with six different flavours on offer for consumers to experience. The ingredients in Oatly's "oatgurt" (oat yogurt) consist of water, oats, potato starch, rapeseed oil, modified potato starch, potato protein, calcium, carbonate, calcium phosphate, acid (lactic acid, malic acid) salt, vitamins (D2, riboflavin and B12) and potassium iodide (Oatly, 2021). The manufacturing of oats into oatgurt includes milling, enzymes, separation, addition of ingredients, heat treatment, homogenizing and packaging. Throughout this process, Oatly is able to retain the loose oat fibres (β-glucans) in their products. The appearance is comparable to that of dairy yogurt, as is the taste, with notes of sweetness and sour, with only two differences: oat flavour and slightly higher bitterness. Cooked cereals may release bitter compounds like pyrroles and thiazoles, posing a challenge for sensory properties of oat yoghurt (Brückner-Gühmann et al., 2019; Rasane et al., 2015). This product does require large volumes of water (2,536 L water/kg oats) (Hoekstra, 2019) limiting its sustainability. The use of upcycled ingredients such as Aquafaba, in lieu of starch (Raikos et al., 2020) may reduce the environmental impact of oat yogurt.

Chia beverage is a new and innovative nutritious beverage, commercially introduced to the global market by a New Zealand company called Chia Sisters. The ingredients in the blackcurrant chia beverage include hydrated chia seeds 89.2% (water and chia seeds), apple concentrate 5.6%, blackcurrant concentrate 5.2% and natural blackcurrant flavour (Chia Sisters, 2021). Chia seeds naturally release soluble fibre upon soaking in water, in the form of mucilage (polysaccharides of xylose, glucose and glucuronic acids) (De Falco et al., 2017). Most of the dietary fibre in chia seeds constitutes of insoluble fibre, which plays a role in prolonged satiety and intestinal functions (Dinçoğlu & Yeşildemir, 2019). Research on natural hydrocolloids have brought the glaze feature of chia seeds to the forefront. Chia seeds have a water holding capacity of 27 times their own weight, with the oil and water retention capacities of chia seeds have been recognised to be higher than thickeners commercially available. Chia mucilage is used as a foam stabiliser, binder or emulsifier in the food industry. Chia gum in the food industry can have important effects, such as amplifying the sensation of food favour on the taste pallet as it has the appropriate fat holding capacity and increasing the overall flavour in food. The partially removed chia gum can be used in sauces, pastries and yoghurt. Chia seeds are highly susceptible to oxidation due to their high quantity of polyunsaturated fatty acids, which means that effective encapsulation methods are required to protect it from oxidative degradation during production and storage (Kulczyński et al., 2019). Chia grows well in arid regions with low quality soils and requires little/if any irrigation once established: 467 L water/kg chia seeds (Berry, 2017). About 1.17 kg CO_2 are released in the production of each kg of chia seeds (Jay, 2021). The processing of chia seeds is relatively simple; after it is harvested, it is then filtered to allow the seeds to separate from the flower and does not require immense energy inputs to prepare the seed for consumers. Therefore, chia beverage can be a simple and tasty way to obtain soluble fibre.

3.3.2 Insoluble

Apart from mushrooms, grains are the dominant raw material to offer innovative sources of insoluble fibre. In decreasing order of insoluble fibre content, examples are: okara flour obtained from spent soybeans of soymilk production (55–58 g/100 g fibre) (Lian et al., 2020; Renewal Mill 2021); defatted sunflower meal, by-product of the oil industry (18 g/100 g fibre) (Grasso et al., 2019; Planetarians, 2021; Tavares et al., 2016); spent grain crackers made with leftover malted barley from beer making (13 g/100 g fibre) (Rutherford & Meyer (2021) (Table 3.4). All these solutions offer cellulose, hemicellulose and lignin, but with different sensory quality and environmental impact.

Okara is an upcycled product from the residue of soymilk production. It contains mostly crude fibre consisting of lignin, hemicellulose and cellulose. It is about 25% protein, containing minimal starch and carbohydrates, making it a favourable additive in food products such as biscuits, by adding fibre without adding a large amount of calories. The high quality protein area allows for good water holding and emulsifying qualities and the peptic polysaccharides fraction aids in thickening acid milk products (O'Toole, 1999). Studies comparing bakery products based on the amount okara content used showed nutritional value consisting of higher protein and fibre content (Lee et al., 2020). The incorporation of okara did however reduce the size of the bread, making it harder and chewier, possibly from a decrease in gas retention and also presented a darker colour. This occurred at wheat flour replacement at 5, 7.5 and 10% dose with okara flour (Ostermann-Porcel et al., 2017). When okara was added in lower does (2% replacement of flour) it improved the moistness of gluten-free bread. This was attributed to high water absorption capacity of soy okara when compared to its flour (8.3 vs. 6.0 g/g) (Lian et al., 2020). Water - footprint is moderate: 2,145 litres of water is used to produce 1 kilogram of soybeans (Mekonnen & Hoekstra, 2011). The carbon footprint of soymilk has been estimated at 0.69 kg CO_2/kg product (Healabel, 2021). Considering that okara is a by-product of soymilk, its carbon footprint should be similar or lower, considering drying into a flour (from up to 80% to as low as 10% moisture) (Guimarães et al., 2018) as a moderate carbon emitter process. Soybean production is moderately sustainable with the two top producers being the US and Brazil. Soy produced in Brazil may be of slight concern due to the deforestation of the Amazon and association with monocropping which is known to cause poor soil structure and encourages the use of chemical fertilizers. The plant-based beverage sector is booming, with products based on legumes (soy, peanut, pea, lupin, cowpea), cereals (rice, corn, oat, spelt), pseudocereals (amaranth, quinoa, teff), seeds (hemp, flax, sesame, sunflower) and nuts (almond, cashew, coconut, hazelnut, pistachio, walnut) (Nawaz et al., 2020). Therefore, the potential for new sources of okara is extraordinary, delivering a variety of nutrients and flavours.

An innovative product that has come from sunflower seeds is Planetarians "SunMeal". It is a plant-based protein flour from upcycled defatted sunflower seeds, marketed as a healthy, cheap, sustainable and nutritional product. Planetariums flour matches the same cost as standard "all-purpose flour" while delivering several nutritional benefits and containing 35% protein, 18% fibre and only 1% fat (Grasso et al., 2019; Planetarians, 2021; Tavares et al., 2016). Initially the company had issues in barriers with this product as it was high in fibre, low in lysine and had a green colour which made the food products unappealing. To overcome this, food scientist had to figure out how to break down the fibre and make the protein palatable for human consumption. This involved balancing the amino acids, enhance the protein quality and eliminate the undesirable green colour. Due to the high fibre content, the SunMeal's taste and texture is not directly equivalent to the typical all-purpose flour, it is best suited to be used in baking mixes and with the correct recipe formulation can be baked into products with little negative impact on the prod-

Table 3.4 Innovative food sources of insoluble fibre: raw materials, bioavailability (fibre profile) and sustainability (water and carbon footprint)

Products	Raw materials	Bioavailability	Sustainability	
		Insoluble fibre profile	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)
Okara flour	Soybeans	55–58 g/100 g cellulose, xylans, xyloglucans	3,018 (soybeans)	0.69 (soymilk)
		Lian et al. (2020), Lu et al. (2013), Renewal Mill (2021)	dos Santos and Naval (2022)	Healabel (2021)
Defatted sunflower meal	Sunflower seeds	18 g/100 g cellulose, hemicellulose, lignin	3,366–3,410 (seeds)	0.88 (seeds)
		Grasso et al. (2019), Planetarians (2021), Tavares et al. (2016)	Mekonnen and Hoekstra (2011), Yousefi et al. (2017)	Yousefi et al. (2017)
Spent grain crackers	Barley malt	13 g/100 g cellulose, hemicellulose, lignin	1,950 (barley malt)	0.96–1.74 (spent grains flour)
		Rutherford & Meyer (2021)	Mekonnen and Hoekstra (2011)	Mussatto et al. (2013)
Mushroom jerky	Mushrooms	8.33 (total fibre) chitin	14–18	0.6–0.7
		Geetha et al. (2021)	Hoekstra et al. (2011)	Hoekstra et al. (2011)

ucts sensory. Being gluten-free and triple the amount of protein to normal flour and the texture is denser the colour of the products are darker. By only replacing 30% of the flour with the meal this allows for minimal impact on the taste and texture of the baked goods while still doubling the protein and fibre content. Being an upcycled ingredient sourced from sunflower oilcake, this makes it favourable in terms of sustainability consumer preference. Sunflower seeds provide 9 g dietary of fibre per 100 g of seeds. About 68% of sunflower seeds fibre is insoluble fibre and the other 32% is soluble. The protein content of sunflower seeds is about 20%. Their high in mostly polyunsaturated fat and high in minerals such as selenium, iron and vitamin E, as well as pantothenic acid which helps the body to metabolize fats, carbs and proteins convert them into energy (Pal, 2011). The mineral contents per 100 g for sunflower seeds consists of 78 mg calcium, 5.25 mg iron, 325 mg magnesium, 660 mg phosphorus, 645 mg potassium, 5 mg zinc and 53.0 μg selenium (Pal, 2011). A sufficient intake of these natural antioxidants and minerals could be beneficial for the human body. Which is where there has been increasing interest of innovated products derived from this ingredient. An example of this is sunflower meal, while it is mostly used for animal feed its nutritional value and properties has increased the interest in using it for human food. Sunflower meal is considered a sustainable product in the aspect that it is the main by-product made from the production of sunflower oil and is up to 36% of the mass of the processed seed. This upcycled product contains 30–50% protein in comparison to just the seeds at 20%. The upcycling of the sunflower meal to a food-grade standard has opened up opportunities to improve the nutritional value of other food products such as the application in biscuits and muffins for example. This is due to its valuable nutritional properties including antioxidants, phenolic content and being able to do so with it high water holding capacity. Environmentally, defatted meal may represent a solution to lower the footprint of sunflower seeds. Their water requirement is high: 3,366–3,410 L/kg product (Mekonnen & Hoekstra, 2011). The carbon footprint is moderate (0.88 kg CO_2/kg product) (Yousefi et al., 2017). Therefore, upcycling its by-product of the oil industry may be an environmentally efficient way to deliver fibre along with seeds bioactives (minerals and vitamins).

An innovated product that has come from spent barley grain is the “Rutherford and Meyer” crackers. These fall under the companies upcycled grain project (UGP), an effort to produce sustainable food and reducing waste and minimizing relying on new resources. Their UGP crackers consist of 43.5% spent barley and 4.7 g of dietary fibre. (Rutherford & Meyer, 2021). Although the company is looked at as a clean label being made in NZ with mostly local ingredients along with being nutritious, high in fibre and an upcycled product it does have a downfall. The taste and texture of the cracker is hard and harsh due to the high fibre content and lack of fat to cover the taste. They could potentially improve sensory of the sharp fibre by grinding the ingredients further or by possibly coating the product with chocolate to increase consumer palatability. Although the product is following favourable market trends in regards to nutrition profile and sustainability, it will need to improve its sensory characteristics to do well in the market. Spent Barley Grain has a high nutrition profile of both protein and fibre being partially high in soluble fibre. Spent barley grain is a lignocellulosic material, consisting of about 70% fibre and 20% protein. It is considered as a good source of dietary fibre, especially for its viscous fibres (its soluble portion contains beta-glucans) which increases cholesterol and fat excretion (Ikram et al., 2017). Again, upcycling can help lower the environmental burden of food production. Barley malt for beer production is known to require about 1,950 L water/kg product (Mekonnen & Hoekstra, 2011). Therefore, finding food applications for its spent grains (leftover after mashing) increases the efficiency of the food chain. What is even more relevant, is the reduced pollution. While barley carbon footprint is around 3.8 kg CO_2/kg product (Healabel, 2021) this number drops to 0.96–1.74 CO_2/kg product for spent grains (Mussatto et al., 2013). The variability is due to different scenarios hypothesised, considering variable technologies for drying of the spent grains. The reason is simple: keeping nutrients inside the food chain allows for efficient supply, thus minimizing emissions.

Finally, mushroom jerky represent an innovative source of chitin (main form of fibre). Its sensory, nutritional and environmental qualities have been described in Sect. 3.3.1. Meaty texture, umami taste, high fibre content and extremely low footprint make this product an excellent fibre choice. The fibre content is lower than that of other innovations (8.3 vs. 18–73 g/100 g) but of high significance as well as of low impact.

3.4 Conclusions

In closing, numerous plant-based foods provide fibre for human nutrition. Whether it is soluble (oligosaccharides, pectin, gums, β-glucans, resistant starch) or insoluble (cellulose, hemicellulose, lignin, chitin), options are available from the plant kingdom. Fruits, vegetables, grains, nuts, seeds and mushrooms all contribute. The environmental impact is generally low, further lowered by the choice of local seasonal ingredients which reduces the carbon footprint of transportation. Among innovative products, inulin powder and oat and chia beverages have seen a surge in interest, due to their combined nutritional benefits (soluble fibre and several bioactives) and textural improvement (juicy and stable). Innovative sources of insoluble fibre mostly come from upcycled ingredients: okara flour from the soymilk industry (and potentially numerous other plant-based beverages), defatted seed meals (sunflower) and spent grains (from beer). Finally, a special mention to mushroom jerky which contain both soluble fibre (β-glucans) and insoluble fibre (chitin) along with several bioactives. Their processing into dense strips allows to deliver nutrition with taste (umami), texture (meaty) and extremely low footprint: 14–18 L water required and 0.6–0.7 kg CO_2 produced for every kg of mushrooms. Drying mushrooms will increase the footprint, but it will still be lower than most of the counterpart.

References

Adeloye, J. B., Osho, H., & Idris, L. O. (2020). Defatted coconut flour improved the bioactive components, dietary fibre, antioxidant and sensory properties of nixtamalized maize flour. *Journal of Agriculture and Food Research, 2*, 100042.

Andersson, U., Rosén, L., Östman, E., Ström, K., Wierup, N., Björck, I., & Holm, C. (2010). Metabolic effects of whole grain wheat and whole grain rye in the C57BL/6J mouse. *Nutrition, 26*(2), 230–239.

Angeli, V., Miguel Silva, P., Crispim Massuela, D., Khan, M. W., Hamar, A., Khajehei, F., et al. (2020). Quinoa (Chenopodium quinoa Willd.): An overview of the potentials of the "Golden grain" and socio-economic and environmental aspects of its cultivation and marketization. *Food, 9*(2), 216.

Atzori, G., Nissim, W. G., Caparrotta, S., Santantoni, F., & Masi, E. (2019). Seawater and water footprint in different cropping systems: A chicory (Cichorium intybus L.) case study. *Agricultural Water Management, 211*, 172–177.

Berry, W. (2017). *Redefining protein: Adjusting diets to protect public health and conserve resources*. USCANADA.

Bongoni, R., Stieger, M., Dekker, M., Steenbekkers, B., & Verkerk, R. (2014). Sensory and health properties of steamed and boiled carrots (Daucus carota ssp. sativus). *International Journal of Food Sciences and Nutrition, 65*(7), 809–815.

Brückner-Gühmann, M., Benthin, A., & Drusch, S. (2019). Enrichment of yoghurt with oat protein fractions: Structure formation, textural properties and sensory evaluation. *Food Hydrocolloids, 86*, 146–153.

Bugaud, C., Deverge, E., Daribo, M.-O., Ribeyre, F., Fils-Lycaon, B., & Mbéguié-A-Mbéguié, D. (2011). Sensory characterisation enabled the first classification of dessert bananas. *Journal of the Science of Food and Agriculture, 91*(6), 992–1000.

Castillo, J. A. A., Apan, A. A., Maraseni, T. N., & Salmo, S. G., III. (2018). Tree biomass quantity, carbon stock and canopy correlates in mangrove forest and land uses that replaced mangroves in Honda Bay, Philippines. *Regional Studies in Marine Science, 24*, 174–183.

Chakraborty, P., Witt, T., Harris, D., Ashton, J., Stokes, J. R., & Smyth, H. E. (2019). Texture and mouthfeel perceptions of a model beverage system containing soluble and insoluble oat bran fibres. *Food Research International, 120*, 62–72.

Chandrashekar, S., Thangaraj, J., & Dasappa, I. (2019). Effect of partially defatted coconut flour on the rheological, physico-sensory characteristics and fatty acid profile of no-added fat rusk. *International Journal of Food Science & Technology, 54*(5), 1769–1776.

Chia Sisters. (2021). https://www.chia.co.nz/pages/chia-nutrition. Accessed 23 July 2021.

Chun, S., Chambers, E., & Han, I. (2020). Development of a sensory flavor lexicon for mushrooms and subsequent characterization of fresh and dried mushrooms. *Food, 9*(8), 980.

Countdown Shop Online. (2021). https://shop.countdown.co.nz/. Accessed 26 July 2021.

Das, A. K., Nanda, P. K., Madane, P., Biswas, S., Das, A., Zhang, W., & Lorenzo, J. M. (2020). A comprehensive review on antioxidant dietary fibre enriched meat-based functional foods. *Trends in Food Science & Technology, 99*, 323–336.

De Falco, B., Amato, M., & Lanzotti, V. (2017). Chia seeds products: An overview. *Phytochemistry Reviews, 16*(4), 745–760.

Dhingra, D., Michael, M., Rajput, H., & Patil, R. T. (2012). Dietary fibre in foods: A review. *Journal of Food Science and Technology, 49*(3), 255–266.

Dinçoğlu, A. H., & Yeşildemir, Ö. (2019). A renewable source as a functional food: Chia seed. *Current Nutrition & Food Science, 15*(4), 327–337.

Dong, L., Wichers, H. J., & Govers, C. (2019). Beneficial health effects of chitin and chitosan. In *Chitin and chitosan: Properties and applications* (pp. 145–167).

dos Santos, J. F. S., & Naval, L. P. (2022). Soy water footprint and socioeconomic development: An analysis in the new agricultural expansion area of the Brazilian cerrado (Brazilian savanna). *Environmental Development, 42*, 100670.

Evans, C. E. L. (2020). Dietary fibre and cardiovascular health: A review of current evidence and policy. *Proceedings of the Nutrition Society, 79*(1), 61–67.

Faravelli. (2021). https://www.faravelli.us/news/26127/quinoa-syrup. Accessed 23 July 2021.

Figueiredo, F., Castanheira, É. G., Feliciano, M., Rodrigues, M. Â., Peres, P., Maia, F., Ramos, A., Carneiro, J., Vlad, C., & Freire, F. (2014). Carbon footprint of apple and pear: Orchards, storage and distribution. *Presentation at Energy for Sustainability, 2013*.

Geetha, P., Sudha, A., & Preetha, P. (2021). Standardization of novel mushroom jerky and consumer preference. Biological forum–an. *International Journal, 13*(2), 362–366.

Gidley, M. J., & Yakubov, G. E. (2019). Functional categorisation of dietary fibre in foods: Beyond 'soluble' vs 'insoluble'. *Trends in Food Science & Technology, 86*, 563–568.

GlobeNewswire. (2019). https://www.globenewswire.com/en/news-release/2019/05/23/1841332/0/en/Inulin-Market-will-grow-at-CAGR-of-10-9-to-hit-2-03-billion-by-2025-Global-Outlook-by-Trends--Size-Share-Regulatory-Framework-Porter-s-Five-Forces-and-Vendor-Landscape-Analysis-Adro.html. Accessed 27 July 2021.

Graf, B. L., Rojas-Silva, P., Rojo, L. E., Delatorre-Herrera, J., Baldeón, M. E., & Raskin, I. (2015). Innovations in health value and functional food development of quinoa (Chenopodium quinoa Willd.). *Comprehensive Reviews in Food Science and Food Safety, 14*(4), 431–445.

Grasso, S., Omoarukhe, E., Wen, X., Papoutsis, K., & Methven, L. (2019). The use of upcycled defatted sunflower seed flour as a functional ingredient in biscuits. *Food, 8*(8), 305.

Greeneatz. (2021). https://www.greeneatz.com/foods-carbon-footprint.html. Accessed 26 July 2021.

Guimarães, R. M., Silva, T. E., Lemes, A. C., Boldrin, M. C. F., da Silva, M. A. P., Silva, F. G., & Egea, M. B. (2018). Okara: A soybean by-product as an alternative to enrich vegetable paste. *LWT, 92*, 593–599.

Healabel. (2021). https://healabel.com/s-ingredients/. Accessed 23 July 2021.

Heusala, H., Sinkko, T., Mogensen, L., & Knudsen, M. T. (2020). Carbon footprint and land use of food products containing oat protein concentrate. *Journal of Cleaner Production, 276*, 122938.

Hoekstra, A. Y. (2014). Sustainable production. In *Green and blue water footprint accounting for beans* (p. 16).

Hoekstra, P. A. (2019). The water footprint of food. *Water for Food*, 49–61.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). *The water footprint assessment manual: Setting the global standard*. Earthscan.

Hossain, I., Imteaz, M. A., & Khastagir, A. (2021). Water footprint: Applying the water footprint assessment method to Australian agriculture. *Journal of the Science of Food and Agriculture.*

Hu, X. Z., Zheng, J. M., Li, X. P., Xu, C., & Zhao, Q. (2014). Chemical composition and sensory characteristics of oat flakes: A comparative study of naked oat flakes from China and hulled oat flakes from western countries. *Journal of Cereal Science, 60*(2), 297–301.

Ikram, S., Huang, L., Zhang, H., Wang, J., & Yin, M. (2017). Composition and nutrient value proposition of brewers spent grain. *Journal of Food Science, 82*(10), 2232–2242.

Jaiswal, B., & Agrawal, M. (2020). Carbon footprints of agriculture sector. In *Carbon footprints* (pp. 81–99). Springer.

Jay, J. (2021). Chapter 2: Carbon footprint of foods. In *Understanding connections between food choices and our environment*. www.healthy.ucla.edu. Accessed 23 July 2021.

Jensen, J. K., & Arlbjørn, J. S. (2014). Product carbon footprint of rye bread. *Journal of Cleaner Production, 82*, 45–57.

Kajla, P., Sharma, A., & Sood, D. R. (2015). Flaxseed—A potential functional food source. *Journal of Food Science and Technology, 52*(4), 1857–1871.

Kalač, P. (2009). Chemical composition and nutritional value of European species of wild growing mushrooms: A review. *Food Chemistry, 113*(1), 9–16.

Kamal-Eldin, A., George, N., Sobti, B., AlRashidi, N., Ghnimi, S., Ali, A. A., et al. (2020). Dietary fiber components, microstructure, and texture of date fruits (Phoenix dactylifera, L.). *Scientific Reports, 10*(1), 1–11.

Kan, L., Nie, S., Hu, J., Wang, S., Cui, S. W., Li, Y., et al. (2017). Nutrients, phytochemicals and antioxidant activities of 26 kidney bean cultivars. *Food and Chemical Toxicology, 108*, 467–477.

Kulczyński, B., Kobus-Cisowska, J., Taczanowski, M., Kmiecik, D., & Gramza-Michałowska, A. (2019). The chemical composition and nutritional value of chia seeds—Current state of knowledge. *Nutrients, 11*(6), 1242.

Lee, D. P. S., Gan, A. X., & Kim, J. E. (2020). Incorporation of biovalorised okara in biscuits: Improvements of nutritional, antioxidant, physical, and sensory properties. *LWT, 134*, 109902.

Li, M. C., Chou, C. F., Hsu, S. C., & Lin, J. S. (2020). Physicochemical characteristics and resistant starch of different varieties of banana from Taiwan. *International Journal of Food Properties, 23*(1), 1168–1175.

Lian, H., Luo, K., Gong, Y., Zhang, S., & Serventi, L. (2020). Okara flours from chickpea and soy are thickeners: Increased dough viscosity and moisture content in gluten-free bread. *International Journal of Food Science & Technology, 55*(2), 805–812.

Licht, T. R., Hansen, M., Bergström, A., Poulsen, M., Krath, B. N., Markowski, J., et al. (2010). Effects of apples and specific apple components on the cecal environment of conventional rats: Role of apple pectin. *BMC Microbiology, 10*(1), 1–11.

Lu, F., Liu, Y., & Li, B. (2013). Okara dietary fiber and hypoglycemic effect of okara foods. *Bioactive Carbohydrates and Dietary Fibre, 2*(2), 126–132.

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences, 15*(5), 1577–1600.

Mirończuk-Chodakowska, I., & Witkowska, A. M. (2020). Evaluation of polish wild mushrooms as beta-glucan sources. *International Journal of Environmental Research and Public Health, 17*(19), 7299.

Mishra, P. K., Tripathi, J., Gupta, S., & Variyar, P. S. (2017). Effect of cooking on aroma profile of red kidney beans (Phaseolus vulgaris) and correlation with sensory quality. *Food Chemistry, 215*, 401–409.

Mudgil, D. (2017). The interaction between insoluble and soluble fiber. In *Dietary fiber for the prevention of cardiovascular disease* (pp. 35–59). Academic.

Mussatto, S. I., Moncada, J., Roberto, I. C., & Cardona, C. A. (2013). Techno-economic analysis for brewer's spent grains use on a biorefinery concept: The Brazilian case. *Bioresource Technology, 148*, 302–310.

Nawaz, M. A., Tan, M., Øiseth, S., & Buckow, R. (2020). An emerging segment of functional legume-based beverages: A review. *Food Reviews International*, 1–39.

Nwafor, I. C., Shale, K., & Achilonu, M. C. (2017). Chemical composition and nutritive benefits of chicory (*Cichorium intybus*) as an ideal complementary and/or alternative livestock feed supplement. *The Scientific World Journal, 2017*.

Nyman, M., Nylander, T., & Asp, N. G. (1993). Degradation of water-soluble fibre polysaccharides in carrots after different types of processing. *Food Chemistry, 47*(2), 169–176.

O'Toole, D. K. (1999). Characteristics and use of okara, the soybean residue from soy milk production a review. *Journal of Agricultural and Food Chemistry, 47*(2), 363–371.

Oatly. (2021). https://www.oatly.com/int/products/oatgurt-natural. Accessed 23 July 2021.

Osterman-Porcel, M.V., Rinaldoni, A. N., Rodriguez-Furlan, L. T., & Campderrros, M. E. (2017). Quality assessment of dried okara as a source of production of gluten-free flour. *Journal of the Science of Food and Agriculture, 97*(9), 2934–2941.

Pal, D. (2011). Sunflower (Helianthus annuus L.) seeds in health and nutrition. In *Nuts and seeds in health and disease prevention* (pp. 1097–1105). Academic.

Parnell, J. A., & Reimer, R. A. (2012). Prebiotic fiber modulation of the gut microbiota improves risk factors for obesity and the metabolic syndrome. *Gut Microbes, 3*(1), 29–34.

Planetarians. (2021). https://www.planetarians.com/. Accessed 23 July 2021.

Primal. (2021). http://www.primalspiritfoods.com/products.php. Accessed 27 July 2021.

Raikos, V., Juskaite, L., Vas, F., & Hayes, H. E. (2020). Physicochemical properties, texture, and probiotic survivability of oat-based yogurt using aquafaba as a gelling agent. *Food Science & Nutrition, 8*(12), 6426–6432.

Rasane, P., Jha, A., Sabikhi, L., Kumar, A., & Unnikrishnan, V. S. (2015). Nutritional advantages of oats and opportunities for its processing as value added foods-a review. *Journal of Food Science and Technology, 52*(2), 662–675.

Renewal Mill. (2021). https://www.renewalmill.com/pages/ingredients. Accessed 23 July 2021.

Roibás, L., Elbehri, A., & Hospido, A. (2015). Evaluating the sustainability of Ecuadorian bananas: Carbon footprint, water usage and wealth distribution along the supply chain. *Sustainable Production and Consumption, 2*, 3–16.

Röös, E., & Karlsson, H. (2013). Effect of eating seasonal on the carbon footprint of Swedish vegetable consumption. *Journal of Cleaner Production, 59*, 63–72.

Rutherford and Meyer. (2021). https://rutherfordandmeyer.co.nz/products/spent-grain-crackers-rock-salt. Accessed 23 July 2021.

Sampaio, A. P. C., Silva, A. K. P., de Amorim, J. R., Santiago, A. D., de Miranda, F. R., Barros, V. S., et al. (2021). Reducing the carbon and water footprints of Brazilian green coconut. *The International Journal of Life Cycle Assessment, 26*(4), 707–723.

Sayed, H. S., & Khalil, S. R. (2017). Effect of chicory inulin extract as a fat replacer on texture and sensory properties of cookies. *Middle East Journal of Applied Sciences, 7*(1), 168–177.

Scanlin, L., & Lewis, K. A. (2017). Quinoa as a sustainable protein source: Production, nutrition, and processing. In *Sustainable protein sources* (pp. 223–238). Academic.

Sensus. (2021). https://www.inspiredbyinulin.com/. Accessed 27 July 2021.

Seppä, L., Railio, J., Mononen, R., Tahvonen, R., & Tuorila, H. (2012). From profiles to practice:

Communicating the sensory characteristics of apples to the wider audience through simplified descriptive profiles. *LWT-Food Science and Technology, 47*(1), 46–55.
Sethi, S., Tyagi, S. K., & Anurag, R. K. (2016). Plant-based milk alternatives an emerging segment of functional beverages: A review. *Journal of Food Science and Technology, 53*(9), 3408–3423.
Sibakov, J., Myllymäki, O., Suortti, T., Kaukovirta-Norja, A., Lehtinen, P., & Poutanen, K. (2013). Comparison of acid and enzymatic hydrolyses of oat bran β-glucan at low water content. *Food Research International, 52*(1), 99–108.
Singh, V., Guizani, N., Al-Zakwani, I., Al-Shamsi, Q., Al-Alawi, A., & Rahman, M. S. (2015). Sensory texture of date fruits as a function of physicochemical properties and its use in date classification. *Acta Alimentaria, 44*(1), 119–125.
Suni, M., Nyman, M., Eriksson, N. A., Björk, L., & Björck, I. (2000). Carbohydrate composition and content of organic acids in fresh and stored apples. *Journal of the Science of Food and Agriculture, 80*(10), 1538–1544.
Svanberg, S. M., Nyman, E. M. G. L., Andersson, R., & Nilsson, T. (1997). Effects of boiling and storage on dietary fibre and digestible carbohydrates in various cultivars of carrots. *Journal of the Science of Food and Agriculture, 73*(2), 245–254.
Svanes, E., & Aronsson, A. K. (2013). Carbon footprint of a Cavendish banana supply chain. *The International Journal of Life Cycle Assessment, 18*(8), 1450–1464.
Taghizadeh-Hesary, F., Rasoulinezhad, E., & Yoshino, N. (2019). Energy and food security: Linkages through price volatility. *Energy Policy, 128*, 796–806.
Tamargo, A., Martin, D., Del Hierro, J. N., Moreno-Arribas, M. V., & Muñoz, L. A. (2020). Intake of soluble fibre from chia seed reduces bioaccessibility of lipids, cholesterol and glucose in the dynamic gastrointestinal model simgi®. *Food Research International, 137*, 109364.
Tavares, B., Sene, L., & Christ, D. (2016). Valorization of sunflower meal through the production of ethanol from the hemicellulosic fraction. *Revista Brasileira de Engenharia Agrícola e Ambiental, 20*, 1036–1042.
TheMarket NZ. (2021). https://themarket.com/nz/p/primal-strip-teriyaki/5574-838455000012?skuid=10513110&utm_source=google&utm_medium=cpc&gclid=EAIaIQobChMI57Kq9pGC8gIVTjsrCh1xXgsbEAQYAyABEgJ9O_D_BwE. Accessed 27 July 2021.
Torbica, A., Škrobot, D., Hajnal, E. J., Belović, M., & Zhang, N. (2019). Sensory and physico-chemical properties of wholegrain wheat bread prepared with selected food by-products. *LWT, 114*, 108414.
Vázquez-Rowe, I., Larrea-Gallegos, G., Villanueva-Rey, P., & Gilardino, A. (2017). Climate change mitigation opportunities based on carbon footprint estimates of dietary patterns in Peru. *PLoS One, 12*(11), e0188182.
Wan, X., Guo, H., Liang, Y., Zhou, C., Liu, Z., Li, K., et al. (2020). The physiological functions and pharmaceutical applications of inulin: A review. *Carbohydrate Polymers, 246*, 116589.
Wossen, T., Berger, T., Haile, M. G., & Troost, C. (2018). Impacts of climate variability and food price volatility on household income and food security of farm households in East and West Africa. *Agricultural Systems, 163*, 7–15.
Yousefi, M., Khoramivafa, M., & Damghani, A. M. (2017). Water footprint and carbon footprint of the energy consumption in sunflower agroecosystems. *Environmental Science and Pollution Research, 24*(24), 19827–19834.
Zhu, F., & Li, J. (2019). Physicochemical and sensory properties of fresh noodles fortified with ground linseed (Linum usitatissimum). *LWT, 101*, 847–853.
Zieliński, H., Michalska, A., Ceglińska, A., & Lamparski, G. (2008). Antioxidant properties and sensory quality of traditional rye bread as affected by the incorporation of flour with different extraction rates in the formulation. *European Food Research and Technology, 226*(4), 671–680.
Ziolkovska, A. (2012). Laws of flaxseed mucilage extraction. *Food Hydrocolloids, 26*(1), 197–204.

4 Protein

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Abstract

Proteins are the building block of the human body. It is recommended to consume 0.8 g of protein per kg of body weight. Quality is equally important: all essential amino acids must be consumed daily. While animal foods (dairy, eggs, fish and meat) offer complete proteins, with high digestibility, their water and carbon footprints present a serious challenge to the planet. Plant foods are more sustainable, yet often incomplete in their amino acidic profile (with cereals low in lysine and legumes low in methionine, for example). Consuming a variety of plant-based protein guarantees access to all essential amino acids. Insects and algae are an area of current interest, although consumer scepticism is present due to unusual looks, taste and challenging logistics (insect farming, algae production). Finally, biotechnology has been implemented to develop mycoprotein and other fermented foods. This could result in high levels of complete protein with low environmental impact.

Keywords

Biotechnology, fish · Footprint · Meat · Plant protein · Protein protein for human nutrition

Protein are essential in human diet. They are the building block of human tissues such as muscles, bones, skin, hair, nails. In addition, they contribute to energy with 3.5 kcal/g, comparably to carbohydrates. Moreover, studies proved the role of specific dietary protein in modulating bone health, cardiovascular disease and diabetes (Qi & Shen, 2020; Shams-White et al., 2017; Tian et al., 2017). Protein are constituted of combinations of up to 20 amino acids, 9 of which are essential, meaning they cannot be synthesised by the human body: histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine (Wu, 2016).

The recommended daily intake is approximately 0.8 g protein/kg body weight (Bilsborough & Mann, 2006; Wu, 2016). This number varies based on age, gender and level of physical activity, reaching 1.6 g protein/kg body weight in adults who exercise intensely (Wu, 2016). Sources of protein are numerous: meat (red, white), seafood (fish, shellfish), plant (seeds,

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nuts, grains and even fruits and vegetables) and insects. Quantity is just as important as quality. Bioavailability refers to the body's ability to digest, absorb and metabolize a certain nutrient or supplement. In terms of protein, bioavailability is measured using a Protein Digestibility Corrected Amino Acid Score (PDCAAS) as a tool to show protein quality. The PDCAAS is a value scored from 0.0 to 1.0 that calculates limiting amino acid score multiplied by protein digestibility (FAO, 2011). For example, cereals like rice and wheat are typically limited in the amount of lysine, whereas legumes like beans and chickpeas are usually low in methionine, thus resulting in low PDCAAS (0.4–0.6). High PDCAAS scores (close to 1.0) are typical of animal protein, with a few exceptions in the plant kingdom (soy and buckwheat for example) (Joye, 2019).

It is important to mention that different sources of protein also delivers a "package" of other nutrients: for example, saturated fats and cholesterol are found in red meat, hormones and vitamins in dairy and eggs, unsaturated fats in fish, phytochemical compounds and antinutrients in grains and mushrooms. It is the matrix that determines protein quality. Finally, the environmental impact must be considered. It is known that the production of animal protein requires more land, water and emits more carbon dioxide (CO_2) than plant protein (Moughan, 2021).

Therefore, this chapter will compare different sources of protein, traditional and innovative, for their protein content and quality, as well as for their environmental impact and consumer acceptability. An example of the modern trajectory of protein-rich food products is depicted in Fig. 4.1.

4.1 Traditional Food Sources of Protein

Protein are found in numerous sources of animal and plant origin. Table 4.1 offers a representative summary of the highest sources of dietary protein. As it can be seen, and perhaps contrary to popular belief, several options are available for those looking to obtain protein. Dairy and meat are the top sources, in terms of quantity: from 25.2 to 33.3 g/100 g of protein in chicken and skim milk powder, respectively (Food Data Central, 2021; NZ Food Composition Data, 2021). Other sources include seeds, nuts and eggs: 7.5–22.4 g/100 g of protein (Food Data Central, 2021; NZ Food Composition Data, 2021). What separates these foods is their environmental impact and consumer acceptability.

Skim milk powder is produced from cow's milk where fat and water have been removed, this increases storage time and allows for lower shipping requirements. Skim milk powder requires the highest resource use of all the proteins in this case study, this is because water is needed to grow the pasture, process the milk, and clean the equipment, dairy production is also heavy in land use and degradation if not carefully managed.. Skim milk powder contains all the essential amino acids and the absorption and bioavailability of the amino acids is very high as there are no anti-nutritive factors in milk (van Lieshout et al., 2020). The cooked flavour of skim milk powder may come from the drying process. The high level of protein and some sugars causes the Maillard reaction, the other flavours are typical of that of milk. However, astringency may be related to a textural defect (Lemieux & Simard, 1994). The price is moderate (1.20 NZD/100 g (Countdown, 2021) thus making it accessible to most consumers.

A more common dairy product is cheese. Let's look, for example, at Parmesan cheese. Approximately 14 litres of milk are needed to produce a kilogram of parmesan; and milk is a resource that takes over six-hundred litres of water to produce one single litre; approximately 5,000 L of water would be needed to produce 1 kilogram of parmesan (Mekonnen & Hoekstra, 2011). Depending on what milk is used, and the ageing process, the total amount of protein per hundred grams varies, with an average value of 32.6 grams of protein per 100 grams (NZ Food Composition Data, 2021). Milk is the main source of protein in cheese, so it is high in all essential amino acids like tyrosine, valine, and especially lysine. Furthermore, these amino acids can be assimilated efficiently as they are hydrolyzed by proteolytic enzymes into peptones, pep-

Fig. 4.1 Representative sources of protein: traditional (beef steak) and innovative (peas)

tides and free amino acids during the ageing process (Summer et al., 2017). Parmesan cheese is known for its piquant flavour, dry, crumbly texture, and strong aroma, and salty aftertaste. This cheese is often used to complete Italian inspired dishes or on a charcuterie board (Loffi et al., 2021). The price bracket varies for Parmesan cheese. For instance, within the Countdown line of supermarkets across New Zealand, the price ranges from $5/100 g to $6.20/100 g (Countdown, 2021). Big factors that contribute to the cost is ageing of cheese and bacteria used. The longer it takes to age, the higher the cost of production. Only certain strains of bacteria can be used to make Parmesan.

When thinking of protein, most people think of meat, particularly read meat such as beef. Its protein content is high, up to 30 g/100 g (NZ Food Composition Data, 2021), and of excellent quality (PDCAAS 1.0) (Ertl et al., 2016). Most consumers appreciate the umami flavour and the tender, juicy texture (Legako et al., 2016). The price is high, anywhere from 2 to 6 NZD/100 g based on the quality (Countdon, 2021). The problem is the environmental weight of such food. The amount of water required is massive: 15,712 L/kg beef (Gerbens-Leenes et al., 2013). This is due to the high demand of cows, which results in large use of plants and water to sustain their growth. In addition, cow farming for meat production causes large production of CO_2: as large as 24 kg CO_2 per kg beef (Vitali et al., 2018). To put it in perspective, dry beans are responsible for production of only 2.0 kg CO_2/kg product (Rahmadi et al., 2021), that is 12 times lower, while delivering comparable protein content of moderate quality (PDCAAS 0.75) (Hoffman & Falvo, 2004). The reason is that plants are digested by cows, their nutrient partially accumulated in the meat and partially excreted via feces and urine. The process is slow, due to cows being ruminants, thus processing foods through four stomachs. In addition, because of forage digestion, cows' metabolism releases methane at variable quantities based on their body weight (Van Lingen et al., 2019). Dietary strategies, such as the introduction of higher quantities of digestible grass and replacement of traditional forage with corn silage, have been trialed to mitigate methane emissions (Van Gastelen et al., 2019). Nonetheless, results were not sufficient.

Tofu is produced from coagulated soybean beverage that is subsequently pressed, this

Table 4.1 Representative food sources of protein: products, nutritional value (quantity, PDCAAS), sustainability (water and carbon footprint) and acceptability (price, taste)

	Nutrition		Sustainability		Taste	
Food products	Protein quantity (g/100 g)	PDCAAS[a]	Water Footprint (L water/kg product)	Carbon Footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory profile
Skim Milk powder	33.3 Food Data Central (2021)	1.00 Chalupa-Krebzdak et al. (2018)	4,745 Mekonnen and Hoekstra (2011)	9.0 Flysjö et al. (2014)	1.20 Countdown (2021)	Milky, sweet, cooked Cheng et al. (2020)
Pumpkin seeds, roasted	32.9 NZ Food Composition Data (2021)	0.97 ESHA Docs (2021)	336 Mekonnen and Hoekstra (2011)	0.14 Schäfer and Blanke (2012)	*2.49* Countdown (2021)	Dark green, hard, nutty taste and aroma Uddin et al. (2016)
Parmesan cheese	32.6 NZ Food Composition Data (2021)	1.00 Summer et al. (2017)	5,000 Mekonnen and Hoekstra (2011)	10.3–16.9 (Grana Padano) Canellada et al. (2018)	*9.00* Countdown (2021)	Light yellow colour, butter aroma, nut smell, salty, pungent, friable Loffi et al. (2021)
Beef steak	29.9 NZ Food Composition Data (2021)	1.00 Ertl et al. (2016)	15,712 Gerbens-Leenes et al. (2013)	24 Vitali et al. (2018)	1.99–5.99 Countdown (2021)	Tender, brown, umami Legako et al. (2016)
Tuna, canned	26.8 NZ Food Composition Data (2021)	1.00, Boye et al. (2012)	Not available	6.1 Rahmadi et al. (2021)	2.31 Countdown (2021)	Fishy, oily, hard, salty, rancid Caponio et al. (2010)
Chicken breast, roasted	25.2 NZ Food Composition Data (2021)	1.00 Burd et al. (2019)	2,872 Gerbens-Leenes et al. (2013)	6.9 Rahmadi et al. (2021)	1.09 Countdown (2021)	Juicy, chewy, chickeny Zhuang and Savage (2010)
Peanut butter	22.4 NZ Food Composition Data (2021)	0.70 Arya et al. (2016)	3,740 Vanham et al. (2020)	2.5 Rahmadi et al. (2021)	1.47–1.66 Countdown (2021)	Brown, glossy, roasted/peanutty, sweet, oily, adhesive, grainy Riveros et al. (2010)
Almonds	20.1 NZ Food Data Composition (2021)	0.44–0.48 House et al. (2019)	13,080 Vanham et al. (2020)	2.6 Volpe et al. (2015)	3.10–3.57 Countdown (2021)	Fruity (150 °C) Nutty (170 °C) Burnt, roasted (190 °C) Lipan et al. (2020)
Eggs, boiled	12.2 NZ Food Composition Data (2021)	1.00 Matsuoka et al. (2019)	3,265 Mekonnen and Hoekstra (2012)	4.8 Rahmadi et al. (2021)	0.70 Countdown (2021)	White (albumen), yellow/orange (yolk), sulphury Yimenu et al. (2017)
Tofu	10.6 NZ Food Composition Data (2021)	1.00 DePalma et al. (2019)	926 Usman (2011)	2.0 Rahmadi et al. (2021)	0.97 Countdown (2021)	Light grey colour, sweet and fermented aroma, sweet/bitter/astringent flavour, firm and elastic texture Kamizake et al. (2018)

(continued)

Table 4.1 (continued)

	Nutrition		Sustainability		Taste	
Food products	Protein quantity (g/100 g)	PDCAAS[a]	Water Footprint (L water/kg product)	Carbon Footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory profile
Greek Yoghurt	9.5 NZ Food Composition Data (2021)	0.95 (whey) ESHA Docs (2021)	672 Vasilaki et al. (2016)	4.5–6.8 Houssard et al. (2020)	0.47–1.50 Countdown (2021)	Fatty, sour, velvety, grainy, smooth Megalemou et al. (2017)
Beans, canned (*Phaseolus vulgaris*)	7.5 NZ Food Composition Data (2021)	0.75 Hoffman and Falvo (2004)	5,053 Mekonnen and Hoekstra (2011)	2.0 Rahmadi et al. (2021)	0.26 Countdown (2021)	Beany, boiled potato, earthy, smoky, sulphury Mishra et al. (2017)

[a]Protein Digestibility Corrected Amino Acid Score

makes soybean the main component that confer tofu its protein. Unlike other plant material, tofu offers a complete source of protein, with a PDCAAS of 1.00 (DePalma et al., 2019), delivering all essential amino acids in high amounts with high digestibility. Much like peas, soybeans are a legume, which means that they can fix their own nitrogen, thus reducing the need for fertiliser. The water requirements are much lower in comparison to milk powder: 926 vs. 4,745 L water/kg product (Mekonnen & Hoekstra, 2011), accounting for harvesting of soybeans and processing into tofu. Similarly, the carbon footprint is very low. The tofu production results in only 2.0 kg of CO_2 emission as opposed to the 9.0 kg CO_2 released by the production of skim milk powder (Flysjö et al., 2014; Rahmadi et al., 2021). The large differences include factors such as pasture growth, cows' diet and maintenance, milk processing and drying. The top five descriptive factors were obtained from a study by Chung and collaborators (2008): beany flavour comes from soybeans, astringency from the tannins and other plant compounds, hardness and roughness from the pressing time, and the saltiness is most likely from the tofu being stored in brine. Due to tofu being historical and heritage driven food, coupled with soybeans being cheap and easy to produce, it means that the price can be significantly lower (0.97 NZD/100 g) (Countdown, 2021) than skim milk powder.

As expected, meat and fish offer large quantities of high-quality protein: 25–30 g/100 g with a PDCAAS score of 1.00 (Table 4.1). The limiting factor is footprint, with water needs in the order of 3–17 times larger than that of plant-based foods. While chicken requires 3 times the amount of water of tofu (2,872 L water for each kg of meat processed), beef reaches the impressive number of 15,712, meaning 17 times more water than tofu (Gerbens-Leenes et al., 2013). This is due to the fact the animals consume plants, such as soya, and later convert it into meat, eggs, and dairy. Therefore, animal-based foods will always require more water than the plant-based counterparts. What is astonishing, is the difference in emissions. For example, the carbon footprint of meat, fish, dairy, and eggs ranges from 4.8 to 24 kg CO_2/kg product (eggs and beef, respectively). This again, is due to the conversion of plant material into meat. These extra steps produce high quality protein but at a cost of the environment. A lower impact choice, within the animal reign, is eggs: on average, 3,265 l water are needed per kg of eggs (Mekonnen & Hoekstra, 2012), producing 4.8 kg CO_2 (Rahmadi et al., 2021). These numbers are moderately high, but closer to those of plant-based foods. Reason laying in chicken's quick conversion of food (they are not ruminants) and abundant production of eggs. In comparison only 0.14–2.6 kg CO_2/kg product are the result of industries producing pumpkin seeds and almonds (Table 4.1).

Almonds look as the least sustainable option among plant-based foods, and not just because of the high footprint (high amounts of water required), but also because of their low protein quality, reported in the range of 0.44–0.48

PDCAAS (House et al., 2019) thus making them a good choice as food in general (energy, fibre, lipids, protein content) but not as source of highly digestible protein.

In this regard, a special mention goes to pumpkin seeds. In the list provided, they are the second highest source of protein: 32.9 g protein/100 g pumpkin seeds (NZ Food Composition Data, 2021). This is common to most nuts and seeds. What is interesting, is the high protein quality: PDCAAS 0.97 (ESHA Docs, 2021). This means that pumpkin protein delivers high levels of all essential amino acids (Vinayashree & Vasu, 2021). Therefore, pumpkin seeds is a potential powerhouse of nutrition. In addition, the environmental footprint of their harvesting and processing is extremely low, even lower than for legumes and nuts: only 336 L water/kg product (Mekonnen & Hoekstra, 2011) and as little as 0.14 kg CO_2 produced for each kg of seeds (Schäfer & Blanke, 2012). This can be explained by the fact the pumpkin seeds are found in a vegetable, pumpkin, which is the actual food product. In some ways, pumpkin seeds can be considered as a by-product of the pumpkin industry. They are found plentiful in pumpkins and contain low levels of moisture. Therefore, processing is minimal, mostly roasting to reduce moisture content and remove any bitterness (Uddin et al., 2016). What is even more fascinating is the versatile functionality of pumpkin protein. It has been shown that pumpkin protein is soluble at mild acidic pH, typical of most foods, comparably to soy protein. Furthermore, pumpkin protein exerts moderate foaming, emulsifying and water absorption properties at high level, similar to those of pea, soy and wheat protein (Vinayashree & Vasu, 2021). The only challenge is sensory: can pumpkin seeds be consumed in similar amounts to dairy, meat, eggs and legumes? Is it feasible to imagine people consuming hundreds of grams of roasted pumpkin seeds? Probably not, unless food innovation were to provide a way to make it more palatable, such as the example of peanut butter, which made peanut consumption easier (Riveros et al., 2010).

4.2 Innovative Food Sources of Protein

As discussed in Sect. 4.2, the main challenges with protein-rich foods are represented by their environmental impact (meat, fish, dairy, eggs), taste (seeds, legumes) and price (beef, nuts). Sustainable food innovation should reduce footprint and price while increasing sensory quality. Numerous options have been proposed: mycoprotein obtained from fermentation, insects, duckweed, legume protein, seaweeds and upcycled ingredients such as spent malt (Table 4.2). Let's investigate one attribute at a time: consumer acceptability, nutrition, sustainability.

4.2.1 Acceptability

Plant-based meals have been a trend that has been booming for a while, especially now with climate change and sustainability also being addressed. Plant-based meals is a global trend and an expected Compound Annual Growth Rate (CAGR) of 7.8% (Associated Press, 2020). Mycoprotein is the raw material for Quorn products. Quorn is a brand that was founded in 1985 and produces a variety of vegetarian and vegan products, with staples such as nuggets and burgers. Mycoprotein is a single-celled protein, derived from fungi, for human consumption (Finnigan et al., 2017). Aerobic fermentation of fungal spores (typically *Fusarium venenatum*) is fermented with glucose and nitrogen. Depending on the type of production, spent grains can be used as a source of glucose and ammonia for nitrogen (Zeece, 2020); this is a great way of recycling food waste. The protein quality is excellent, reaching a PDCAAS score of 0.99 (Finnigan et al., 2017). For a product to be successful, it must appeal to customers in terms of sensory and price. For example, Quorn mince (a vegan alternative to beef mince) is priced at \$2.83/100 g. On the other hand, the average price of premium beef mince from Countdown is \$2.57/100 g (Countdown, 2021). This price difference is insignificant, meaning the median earning consumer would have access to this

Table 4.2 Innovative food sources of protein: raw materials, bioavailability (PDCAAS) and sustainability (water and carbon footprint)

Products	Raw materials	Bioavailability	Sustainability	
		PDCAAS[a]	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)
Mycoprotein	Mycoprotein	0.99 Finnigan et al. (2017)	500 Smetana et al. (2018)	1.14 Smetana et al. (2018)
Insect flour	Crickets	0.91 Halloran et al. (2017)	420 Halloran et al. (2017)	2.57 Halloran et al. (2017)
Duckweed	Lemenaceae	0.89 Kaplan et al. (2019)	Not available	−3.0 Duckweed absorbs three times the volume produced of CO_2 Mohedano et al. (2019)
Pea protein	Peas	0.68–0.71 Nosworthy et al., 2017	595 Mekonnen and Hoekstra (2011)	0.49 Nette et al. (2016)
Seaweed	Microalgae	0.64 Wang et al. (2020)	960 Martins et al. (2018)	1.72 Martins et al. (2018)
Spent grain Bar	Spent barley malt	0.61 Nitrayová et al. (2018)	1,423 Mekonnen and Hoekstra (2011)	0.29–1.74 Cimini and Moresi (2016); Mussatto et al. (2013)

[a]Protein Digestibility Corrected Amino Acid Score

product. In comparison to beef mince, Quorn mince has a very mild, almost neutral flavour. The appearance resembles fried/steamed mince, however, the texture is slightly chewy. To counteract this, Quorn processes the mycoprotein into convenience products such as nuggets, burgers, and chilli mince. The only drawback is that this product is sold in supermarket freezer sections. Often this is associated with the food being not as fresh (like organic produce) and hence not as beneficial. Mycoprotein has an extremely high PDCAAS value, of approximately 0.996 (Finnigan et al., 2017). However, methionine and cystine are two of the limiting amino acids found in mycoprotein. When the protein digestibility was initially calculated, a value above 1.0 was determined. However, the data suggested that approximately 10% of the glucosamine nitrogen is possibly digested by the small intestine, as intestinal mucus contains some glucosamine. Once the mycoprotein is ready it is seasoned, mixed egg protein, or plant protein, to help bind the mix into a dough-like form. It is then steam-cooked for about 30 minutes, and chilled, before being shaped into a variety of products. Studies have shown the average digestibility of Quorn is approximately 0.91 (Schweiggert-Weisz et al., 2020). This change is minimal and could be due to the processing but is likely calculation discrepancies. Additionally, a study conducted in 2018 showed that it takes about 500 L of water to produce a kilogram of mycoprotein (Smetana et al., 2018). Furthermore, to produce 1 kg of mycoprotein, 1.14 kg CO_2/kg is produced, and 1.72 kg CO_2/kg once it is processed into Quorn mince (Harrison & Johnson, 2018).

The global insect market is expected to have a Compound Annual Growth Rate (CAGR) of 23.8% from 2018 to 2023 (Ebenebe et al., 2020). This may be due to the increasing global population and the search for alternative food sources. Insect farming and rearing are already practiced in countries such as Thailand, Singapore, and China (Amadi & Kiin-Kabari, 2016). By using the CAGR insect farming has the opportunity to provide income to otherwise economically disadvantaged countries. Because of the low labour and production costs in these countries, there would be a symbiotic economic relationship of the low production cost for importers and income for exporters, leading to good price sustainability. The main negative that this product faces are consumer perception, mainly stemming from the Western world. Insects have long been a staple in Asian and African cultures, as the product pushes into the west it may not be as accepted. Burt and collaborators (Burt et al., 2020) found that the consumer acceptance of using cricket flour as a substitute for all-purpose flour in muffins was very low, however, the sensory characteristics were improved by using cricket flour. This highlights the opportunity of cricket flour following consumer acceptance. Crickets have the lowest water requirements of the three protein sources coming in at 420 L of water per kilogram of product and 2.57 kg CO2 produced per kg of crickets (Halloran et al., 2017), this is because crickets can get most of their water from the food they eat. When invertebrates eat fresh fruit and vegetables this is usually enough to sustain their water requirements, if invertebrates require freshwater, the amount is to be so small that they do not drown in it (Inostroza et al., 2016). This is important because although the feed uses water, the fresh-water requirement is very low and therefore sustainable. Insects can transform low value or unwanted organic material into high-quality nutrient food (van Huis & Oonincx, 2017). This means that crickets can feed on food that may not be accepted by the consumer, using food that would otherwise go to waste. Cricket flours have a high PCDAAS score at 0.91, this is similar to that of beef and soy (van Vliet et al., 2015). This means that the proteins and specifically, amino acids in crickets are highly digestible. Crickets have high levels of isoleucine, leucine and valine, the limiting amino acid is tryptophan (Köhler et al., 2019). So, although crickets are a complete protein, they are limited in at least one of the essential amino acids. Another important factor to consider is the effect of processing on the protein content of the products. Cricket powders that were treated with high-temperature processing methods showed sufficient thermostability regarding protein (Montowska et al., 2019). This is important because it means the protein digestibility is not compromised through thermal processing methods.

Another interesting source of protein is duckweed, also known as water lentils. Duckweed is commonly eaten in southeastern Asian countries such as Laos, Myanmar and Thailand and it's gaining attention from researchers and industries across the world (de Beukelaar et al., 2019). Duckweed is a plant belonging to the family *Lemnaceae*, subfamilies of *Landoltia, Lemna, Pirodela, Wolfiella* and *Wolffia* (Bog et al., 2019). Its appearance is round, without roots (Kaplan et al., 2019) resembling green lentils in colour and shape, from which the name water lentils originated. It floats on the water surface of ponds and lakes, sometimes even in low current rivers. Duckweed is one of the fastest growing plants, with the unique ability to produce large quantities of nutrients, with a staggering protein concentration of 20–43% (Appenroth et al., 2017; Bog et al., 2019; de Beukelaar et al., 2019). Furthermore, duckweed protein is highly bioavailable, with a PDCAAS score of 0.89, due to high concentrations of all essential amino acids (lysine, methionine, cysteine, phenylalanine, and tyrosine, in particular) with high digestibility (Appenroth et al., 2017; Kaplan et al., 2019). Due to the limited information available on this food, no data was found on its environmental footprint. The carbon footprint of the duckweed itself can be considered as negative due to its ability to absorb carbon dioxide. Processing into food ingredients may generate carbon emissions. In terms of consumer acceptability, studies have shown high liking for duckweed, with panellists considering this plant material as a vegetable, rather than a protein source, thus increasing its acceptability in vegetable-containing meals (de Beukelaar et al., 2019). Sensory quality and the rapid production of biomass seems to indicate a promising future for duckweed farming, but assessment of its footprint is needed to evaluate its sustainability.

Pea protein is expected to show a 12% CAGR from 2021 to 2026 (Arteaga et al., 2021). Additionally, pea protein is a viable and functional protein source that contains around 70% w/w protein (Qamar et al., 2019). This is important because it shows that the pea protein extraction process is effective and proves viability and scalability. Pea protein also has good sensory characteristics apart from some bitter notes which may play a role in the way they are added to food (Arteaga et al., 2020). Careful use of pea protein additions in food should be able to mitigate these flavours and lead to full consumer sensory acceptability. Peas have a moderate water requirement: it takes 595 L of water to produce one kilogram of product. This is exponentially higher than the water requirement for cricket production. The water use for peas also may be high because the farmers producing peas need to keep the availability of water high. This is because if the pea plant becomes water-stressed during key developmental and growth stages there will be a reduction in the yield of the seed (Martin et al., 1994). It only produces 0.49 kg CO_2 per kg peas (Nette et al., 2016). Lastly, peas have a moderate PCDAAS (0.68–0.71) depending on varieties. Peas contain all the essential acids however they are not complete due to their low levels of methionine (Gorissen et al., 2018). Like grains, legumes such as peas carry anti-nutritive factors which may lead to decreased absorption of protein. An example of an amino acid inhibitor in peas are trypsin inhibitors, trypsin inhibitors work by being a competitive substrate for trypsin and reduce protein digestion, however, cooking, soaking, and processing peas help to remove these factors (Wang et al., 1998). This is an important factor to consider during processing to enhance the bioavailability of the protein in peas. The protein content of peas is not affected by thermal or high-pressure processing such as the extrusion process (Alonso et al., 2001). This aids the extraction of pea protein as it allows a range of processes to be used without compromising the amino acid profiles.

Microalgae are a unique photosynthetic organism made up of phycobiliproteins (Bleakley & Hayes, 2017). Microalgae are fermented in bioreactors and can be fed with spent grains, okara, and molasses. Once again, this is a way of recycling industrial food waste, whilst providing the microalgae with sources of carbon and nitrogen. An expected CAGR of 6.5% is estimated for microalgae, and maybe once this company goes global, more products will be available (Yahoo Finance, 2021). This novel technology can produce a white powder that is odourless and can be used as a base for plant-based milk. Whereas, the brown powder has a seaweed aroma and provides an umami flavour; this can be used as a meat replacer for seafood and chicken products. Currently, the initial price of protein flour is just over NZD 4.00/100 g; with prices expected to drop to \$0.84 within 3 years, and then further dropping to \$0.28 within 10 years as production scales up (Begum, 2020). Fermentation of microalgae results in a high PDCAAS of 0.81, however, the limiting amino acids in *Chlorella spp*. is histidine and isoleucine (Wang et al., 2020). Even though the amount of histidine and isoleucine is restricted, microalgae are digestible; partially because nutrients become more bioavailable after fermentation. Fermentation reduces the levels of non-nutritive compounds that inhibit digestive enzymes (e.g., trypsin and chymotrypsin inhibitors) and promote protein crosslinking (e.g., phenolic and tannin compounds), additionally production of microbial proteases partially degrades and release some of the proteins (Çabuk et al., 2018). When microalgae are processed into flours, like Sophie's Bionutrients, the cell walls are mechanically ruptured. A study conducted in 2020 investigated PDCAAS of various algae and showed that mechanically ruptured cell walls significantly improved digestibility (Wang et al., 2020). This is because the cellulose cell wall of algae cannot be digested by humans; so true protein digestibility was initially 0.64 which then increased to 0.81 once *Chlorella Sorokiniana* algae were mechanically ruptured. A study on the water footprint of growing microalgae in multi-tubular photobioreactor was conducted showing total water of approximately 0.96 m^3/kg dry biomass, which is 960 L required to produce 1 kg of dry biomass (Martins et al., 2018). Furthermore, 90% of the water can be recycled in production or can be upcycled into biofuel (Martins et al., 2018). Along with this study, a carbon footprint of the microalgae production was done in the same pilot-scale multi-tubular photobioreactor. It was discovered that a total of 1.72 kg CO_2/kg dry biomass is created (Martins et al., 2018).

Brewers spent grains are a byproduct of wort extraction from beer brewing and are rich in hydrophobic protein, fiber, and trace minerals (Ikram et al., 2017). The spent grains are seen as an opportunity to upcycle and use as an adjunct to fortify foods, leading to its rise in uses such as the ReGrained extruded snacks. Stojceska et al. (2008) found that by adding spent grains to extruded snacks the protein content could be enhanced significantly. Although barley uses a lot of water to produce these snacks, they are environmentally friendly as they are upcycled from material that would otherwise be seen as waste. This makes snacks price effective and environmentally sustainable, ReGrained itself boasting multiple certifications such as Non-GMO and Organic (Regrained, 2021). This leads to consumer acceptance; however, the sensory characteristics may need to be enhanced to gain preference. Although an older study, it was found that an increase in the addition of brewers spent grains to 15% of the extrudate deteriorated the sensory characteristics of the product (Makowska et al., 2013). This means that spent grains may deliver some negative organoleptic properties and care should be taken to negate this. Barley has a low PCDAAS score at 0.61. This means that although high amounts of protein can be put into food there may be limiting amino acids or low digestibility. In addition, soluble protein dissolve in water (to make beer), thus leaving only some protein in the spent grains. This may be due to cereals containing anti-nutritive factors such as polyphenolic tannins which bind to proteins and enzymes and in turn, reduce the bioavailability and absorption of protein (Björck et al., 2012). This is important to consider when using barley in food products specifically with nutritive protein claims. Barley has an almost complete amino acid profile with lysine being the limiting amino acid, interestingly, brewers spent grains contains high amounts of lysine and histidine and low amounts of threonine, tryptophan, and methionine (Lynch et al., 2016; Sauer et al., 1974). This implies that the thermal process of wort extraction affects the amino acid profile of barley. Lastly, barley has the highest water use for the three protein sources, it takes 1,423 L of water to produce one kilogram of product. Unlike peas, cereals like barley have a shallow rooting system and don't have the same access to the volume of water. Much like peas, however, the yield of barley is dependent on the plant not undergoing water stress. When barley becomes water-stressed, the time for ear emergence increases and in turn decreases the yield of the ear (González et al., 2008). Because of this, it is important to keep water in the soil when growing barley, and because of the shallow roots, there is a higher water use than peas.

4.3 Conclusions

In closing, protein is an essential macronutrient that can be obtained from a wide variety of foods. They support the development of healthy muscles, bones, skin and hair, while providing energy and modulating human metabolism. Quantity as well as quality are important. All nine essential amino acids should be present in a diet, not necessarily in each meal, but definitely in a daily plan. Also, the matrix is crucial. Different protein-rich foods exert different health effects on human, either positive or negative, based on the amount consumed and based on the matrix (fats, phytochemicals, hormones and so on). Traditional sources of protein include dairy (milk, milk powder, cheese and yoghurt), eggs, meat (beef, poultry), fish, legumes, seeds and nuts. Recently, consumer attention has shifted toward alternative protein such as mycoprotein, insects, duckweed, legume protein, algae and upcycled ingredients (spent grains, defatted flours). Animal sources often match excellent bioavailability (high PDCAAS score) with low sustainability (high water and carbon footprints). Plant protein offer plenty quantity and are more sustainable but sometimes less complete in essential amino acids. Exceptions are available (soy, pumpkin seeds) but limited by their sensory profile. Therefore, a multidisciplinary approach is encouraged. Consumers should choose more plant-based protein from a variety of sources (to achieve complete and balanced amino acid intake). Second, food manufacturers should improve their technology to fully unlock the potential of nutrient-dense foods such as pumpkin seeds. In addition, they may open to new, less explored options, such as mycoprotein, duckweed, and perhaps insects and upcycled ingredients (the last two might face more consumer adversity). Overall, protein sources are numerous and quality is available. It is a matter of reducing the environmental footprint and choosing from a wide variety of options, preferably plant-based.

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References

Alonso, R., Rubio, L. A., Muzquiz, M., & Marzo, F. (2001). The effect of extrusion cooking on mineral bioavailability in pea and kidney bean seed meals. *Animal Feed Science and Technology, 94*(1–2), 1–13.

Amadi, E. N., & Kiin-Kabari, D. B. (2016). Nutritional composition and microbiology of some edible insects commonly eaten in Africa, hurdles and future prospects: A critical review. *Journal of Food: Microbiology, Safety & Hygiene, 1*(1), 1000107.

Appenroth, K. J., Sree, K. S., Böhm, V., Hammann, S., Vetter, W., Leiterer, M., & Jahreis, G. (2017). Nutritional value of duckweeds (Lemnaceae) as human food. *Food Chemistry, 217*, 266–273.

Arteaga, V. G., Guardia, M. A., Muranyi, I., Eisner, P., & Schweiggert-Weisz, U. (2020). Effect of enzymatic hydrolysis on molecular weight distribution, techno-functional properties and sensory perception of pea protein isolates. *Innovative Food Science & Emerging Technologies, 65*, 102449.

Arteaga, V. G., Kraus, S., Schott, M., Muranyi, I., Schweiggert-Weisz, U., & Eisner, P. (2021). Screening of twelve pea (Pisum sativum L.) cultivars and their isolates focusing on the protein characterization, functionality, and sensory profiles. *Foods, 10*(4), 758.

Arya, S. S., Salve, A. R., & Chauhan, S. (2016). Peanuts as functional food: A review. *Journal of Food Science and Technology, 53*(1), 31–41.

Associated Press. (2020). *Meat substitute market size headed to $8.1 billion by 2026 at 7.8% CAGR: The demand is expected to surge during the Covid-19 pandemic*. https://apnews.com/press-release/wired-release/807704f8e0c57e394480265ad5edb0d6. Accessed on 2021, August 4.

Begum, S. (2020). *Singapore agri-food start-up hopes to feed astronauts with microalgae*. URL: https://www.straitstimes.com/singapore/president-halimah-yacob-visits-agri-food-start-up-that-creates-protein-flour-and-crab. Accessed 2021, August 4.

Bilsborough, S., & Mann, N. (2006). A review of issues of dietary protein intake in humans. *International Journal of Sport Nutrition and Exercise Metabolism, 16*(2), 129–152.

Björck, I., Östman, E., Kristensen, M., Anson, N. M., Price, R. K., Haenen, G. R., et al. (2012). Cereal grains for nutrition and health benefits: Overview of results from in vitro, animal and human studies in the HEALTHGRAIN project. *Trends in Food Science & Technology, 25*(2), 87–100.

Bleakley, S., & Hayes, M. (2017). Algal proteins: Extraction, application, and challenges concerning production. *Foods (Basel, Switzerland), 6*(5), 33.

Bog, M., Appenroth, K. J., & Sree, K. S. (2019). Duckweed (Lemnaceae): Its molecular taxonomy. *Frontiers in Sustainable Food Systems, 3*, 117.

Boye, J., Wijesinha-Bettoni, R., & Burlingame, B. (2012). Protein quality evaluation twenty years after the introduction of the protein digestibility corrected amino acid score method. *British Journal of Nutrition, 108*(S2), S183–S211.

Burd, N. A., Beals, J. W., Martinez, I. G., Salvador, A. F., & Skinner, S. K. (2019). Food-first approach to enhance the regulation of post-exercise skeletal muscle protein synthesis and remodeling. *Sports Medicine, 49*(1), 59–68.

Burt, K. G., Kotao, T., Lopez, I., Koeppel, J., Goldstein, A., Samuel, L., & Stopler, M. (2020). Acceptance of using cricket flour as a low carbohydrate, high protein, sustainable substitute for all-purpose flour in muffins. *Journal of Culinary Science & Technology, 18*(3), 201–213.

Çabuk, B., Nosworthy, M. G., Stone, A. K., Korber, D. R., Tanaka, T., House, J. D., & Nickerson, M. T. (2018). Effect of fermentation on the protein digestibility and levels of non-nutritive compounds of pea protein concentrate. Food technology and biotechnology, 56(2), 257.

Canellada, F., Laca, A., Laca, A., & Díaz, M. (2018). Environmental impact of cheese production: A case study of a small-scale factory in southern Europe and global overview of carbon footprint. *Science of The Total Environment, 635*, 167–177.

Caponio, F., Bilancia, M. T., Summo, C., Gomes, T., & Pasqualone, A. (2010). A survey of in-oil canned tuna quality by sensory analysis and the determination of the oxidative degradation of the liquid medium. *International Journal of Food Properties, 13*(4), 672–681.

Chung, J. A., Lee, H. S., & Chung, S. J. (2008). Developing sensory lexicons for tofu. Food Quality and Culture, 2(1), 27–31..

Chalupa-Krebzdak, S., Long, C. J., & Bohrer, B. M. (2018). Nutrient density and nutritional value of milk and plant-based milk alternatives. *International Dairy Journal, 87*, 84–92.

Cheng, Z., O'Sullivan, M. G., Kerry, J. P., Drake, M. A., Miao, S., Kaibo, D., & Kilcawley, K. N. (2020). A cross-cultural sensory analysis of skim powdered milk produced from pasture and non-pasture diets. *Food Research International, 138*, 109749.

Cimini, A., & Moresi, M. (2016). Carbon footprint of a pale lager packed in different formats: Assessment and sensitivity analysis based on transparent data. *Journal of Cleaner Production, 112*, 4196–4213.

Countdown. (2021). URL: https://shop.countdown.co.nz/. Accessed 2021, July 29.

de Beukelaar, M. F., Zeinstra, G. G., Mes, J. J., & Fischer, A. R. (2019). Duckweed as human food. The influence of meal context and information on duckweed acceptability of Dutch consumers. *Food Quality and Preference, 71*, 76–86.

DePalma, K., Smith, B., & McDonald, A. G. (2019). Effect of processing conditions, biochemical properties, and microstructure on tofu production from yellow field peas (*Pisum sativum*). *Journal of Food Science, 84*(12), 3463–3472.

Ebenebe, C. I., Ibitoye, O. S., Amobi, I. M., & Okpoko, V. O. (2020). African edible insect consumption market. In *African edible insects as alternative source of food, oil, protein and bioactive components* (pp. 19–51). Springer.

Ertl, P., Knaus, W., & Zollitsch, W. (2016). An approach to including protein quality when assessing the net contribution of livestock to human food supply. *Animal, 10*(11), 1883–1889.

ESHA Docs. (2021). URL: https://esharesearch.atlassian.net/wiki/spaces/GENFOOD/pages/738820126/Protein+Digestibility. Accessed on 2021, July 29.

FAO. (2011). *Dietary protein quality evaluation in human nutrition*, FAO Food And Nutrition Paper, ISSN 0254-4725. http://www.fao.org/ag/humannutrition/35978-02317b979a686a57aa4593304ffc17f06.pdf

Finnigan, T., Needham, L., & Abbott, C. (2017). Mycoprotein: A healthy new protein with a low environmental impact. In *Sustainable protein sources* (pp. 305–325). Academic Press.

Flysjö, A., Thrane, M., & Hermansen, J. E. (2014). Method to assess the carbon footprint at product level in the dairy industry. *International Dairy Journal, 34*(1), 86–92.

Food Data Central. (2021). URL: https://fdc.nal.usda.gov/. Accessed 2021, July 29.

Gerbens-Leenes, P. W., Mekonnen, M. M., & Hoekstra, A. Y. (2013). The water footprint of poultry, pork and beef: A comparative study in different countries and production systems. *Water Resources and Industry, 1*, 25–36.

González, A., Martin, I., & Ayerbe, L. (2008). Yield and osmotic adjustment capacity of barley under terminal water-stress conditions. *Journal of Agronomy and Crop Science, 194*(2), 81–91.

Gorissen, S. H., Crombag, J. J., Senden, J. M., Waterval, W. H., Bierau, J., Verdijk, L. B., & van Loon, L. J. (2018). Protein content and amino acid composition of commercially available plant-based protein isolates. *Amino Acids, 50*(12), 1685–1695.

Halloran, A., Hanboonsong, Y., Roos, N., & Bruun, S. (2017). Life cycle assessment of cricket farming in North-Eastern Thailand. *Journal of Cleaner Production, 156*, 83–94.

Harrison, R., & Johnson, R. (2018). Mycoprotein production and food sustainability. *Microbiology Today, Microbes and Food, 45*(3), 118–121.

Hoffman, J. R., & Falvo, M. J. (2004). Protein–which is best? *Journal of Sports Science & Medicine, 3*(3), 118.

House, J. D., Hill, K., Neufeld, J., Franczyk, A., & Nosworthy, M. G. (2019). Determination of the protein quality of almonds (Prunus dulcis L.) as assessed by in vitro and in vivo methodologies. *Food Science & Nutrition, 7*(9), 2932–2938.

Houssard, C., Maxime, D., Benoit, S., Pouliot, Y., & Margni, M. (2020). Comparative life cycle assessment of five Greek yogurt production systems: A perspective beyond the plant boundaries. *Sustainability, 12*(21), 9141.

Inostroza, P. A., Wicht, A. J., Huber, T., Nagy, C., Brack, W., & Krauss, M. (2016). Body burden of pesticides and wastewater-derived pollutants on freshwater invertebrates: method development and application in the Danube River. Environmental pollution, 214, 77–85.

Ikram, S., Huang, L., Zhang, H., Wang, J., & Yin, M. (2017). Composition and nutrient value proposition of brewers spent grain. *Journal of Food Science, 82*(10), 2232–2242.

Joye, I. (2019). Protein digestibility of cereal products. *Foods, 8*(6), 199.

Kamizake, N. K. K., Silva, L. C. P., & Prudencio, S. H. (2018). Impact of soybean aging conditions on tofu sensory characteristics and acceptance. *Journal of the Science of Food and Agriculture, 98*(3), 1132–1139.

Kaplan, A., Zelicha, H., Tsaban, G., Meir, A. Y., Rinott, E., Kovsan, J., et al. (2019). Protein bioavailability of Wolffia globosa duckweed, a novel aquatic plant–A randomized controlled trial. *Clinical Nutrition, 38*(6), 2576–2582.

Köhler, R., Kariuki, L., Lambert, C., & Biesalski, H. K. (2019). Protein, amino acid and mineral composition of some edible insects from Thailand. *Journal of Asia-Pacific Entomology, 22*(1), 372–378.

Legako, J. F., Dinh, T. T. N., Miller, M. F., Adhikari, K., & Brooks, J. C. (2016). Consumer palatability scores, sensory descriptive attributes, and volatile compounds of grilled beef steaks from three USDA Quality Grades. *Meat Science, 112*, 77–85.

Lemieux, L., & Simard, R. E. (1994). Astringency, a textural defect in dairy products. *Le Lait, 74*(3), 217–240.

Lipan, L., Cano-Lamadrid, M., Vázquez-Araújo, L., Łyczko, J., Moriana, A., Hernández, F., et al. (2020). Optimization of roasting conditions in hydroSOStainable almonds using volatile and descriptive sensory profiles and consumer acceptance. *Journal of Food Science, 85*(11), 3969–3980.

Loffi, C., Bortolazzo, E., Garavaldi, A., Musi, V., Reverberi, P., Galaverna, G., et al. (2021). Reduction in the brining time in Parmigiano Reggiano cheese production minimally affects proteolysis, with no effect on sensory properties. *Foods, 10*(4), 770.

Lynch, K. M., Steffen, E. J., & Arendt, E. K. (2016). Brewers' spent grain: A review with an emphasis on food and health. *Journal of the Institute of Brewing, 122*(4), 553–568.

Makowska, A., Mildner-Szkudlarz, S., & Obuchowski, W. (2013). Effect of brewer's spent grain addition on properties of corn extrudates with an increased dietary fibre content. *Polish Journal of Food and Nutrition Sciences, 63*(1).

Martin, I., Tenorio, J. L., & Ayerbe, L. (1994). Yield, growth, and water use of conventional and semileafless peas in semiarid environments. *Crop Science, 34*(6), 1576–1583.

Martins, A. A., Marques, F., Cameira, M., Santos, E., Badenes, S., Costa, L., et al. (2018). Water footprint of microalgae cultivation in photobioreactor. *Energy Procedia, 153*, 426–431.

Matsuoka, R., Kurihara, H., Nishijima, N., Oda, Y., & Handa, A. (2019). Egg white hydrolysate retains the nutritional value of proteins and is quickly absorbed in rats. *The Scientific World Journal, 2019*, 5475302.

Megalemou, K., Sioriki, E., Lordan, R., Dermiki, M., Nasopoulou, C., & Zabetakis, I. (2017). Evaluation of sensory and in vitro anti-thrombotic properties of traditional Greek yogurts derived from different types of milk. *Heliyon, 3*(1), e00227.

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences, 15*(5), 1577–1600.

Mekonnen, M. M., & Hoekstra, A. Y. (2012). A global assessment of the water footprint of farm animal products. *Ecosystems, 15*(3), 401–415.

Mishra, P. K., Tripathi, J., Gupta, S., & Variyar, P. S. (2017). Effect of cooking on aroma profile of red kidney beans (Phaseolus vulgaris) and correlation with sensory quality. *Food Chemistry, 215*, 401–409.

Mohedano, R. A., Tonon, G., Costa, R. H., Pelissari, C., & Belli Filho, P. (2019). Does duckweed ponds used for wastewater treatment emit or sequester greenhouse gases? *Science of The Total Environment, 691*, 1043–1050.

Montowska, M., Kowalczewski, P. Ł., Rybicka, I., & Fornal, E. (2019). Nutritional value, protein and peptide composition of edible cricket powders. *Food Chemistry, 289*, 130–138.

Moughan, P. J. (2021). Population protein intakes and food sustainability indices: The metrics matter. *Global Food Security, 29*, 100548.

Mussatto, S. I., Moncada, J., Roberto, I. C., & Cardona, C. A. (2013). Techno-economic analysis for brewer's spent grains use on a biorefinery concept: The Brazilian case. *Bioresource Technology, 148*, 302–310.

Nette, A., Wolf, P., Schlüter, O., & Meyer-Aurich, A. (2016). A comparison of carbon footprint and production cost of different pasta products based on whole egg and pea flour. *Foods, 5*(1), 17.

New Zealand Food Composition Data. (2021). URL: https://www.foodcomposition.co.nz/. Accessed 2021, July 29.

Nitrayová, S., Brestenský, M., & Patráš, P. (2018). Comparison of two methods of protein quality evaluation in rice, rye and barley as food protein sources in human nutrition. *Potravinarstvo, 12(1), 762–766.*

Nosworthy, M. G., Franczyk, A. J., Medina, G., Neufeld, J., Appah, P., Utioh, A., et al. (2017). Effect of processing on the in vitro and in vivo protein quality of yellow and green split peas (Pisum sativum). *Journal of Agricultural and Food Chemistry, 65*(35), 7790–7796.

Qamar, S., Bhandari, B., & Prakash, S. (2019). Effect of different homogenisation methods and UHT processing on the stability of pea protein emulsion. *Food Research International, 116*, 1374–1385.

Qi, X. X., & Shen, P. (2020). Associations of dietary protein intake with all-cause, cardiovascular disease, and cancer mortality: A systematic review and meta-analysis of cohort studies. *Nutrition, Metabolism and Cardiovascular Diseases, 30*(7), 1094–1105.

Rahmadi, P., Widodo, A. A., & Marzuki, R. (2021, July). Carbon footprint of tuna and tuna like production landed based at Bitung fish port. In *IOP Conference Series: Earth and Environmental Science* (Vol. 800, No. 1, p. 012004). IOP Publishing.

Regrained. (2021). URL: https://www.regrained.com/. Accessed 2021, August 4.

Riveros, C. G., Mestrallet, M. G., Gayol, M. F., Quiroga, P. R., Nepote, V., & Grosso, N. R. (2010). Effect of storage on chemical and sensory profiles of peanut pastes prepared with high-oleic and normal peanuts. *Journal of the Science of Food and Agriculture, 90*(15), 2694–2699.

Sauer, W. C., Giovannetti, P. M., & Stothers, S. C. (1974). Availability of amino acids from barley, wheat, triticale, and soybean meal for growing pigs. *Canadian Journal of Animal Science, 54*(1), 97–105.

Schäfer, F., & Blanke, M. (2012). Farming and marketing system affects carbon and water footprint–A case study using Hokaido pumpkin. *Journal of Cleaner Production, 28*, 113–119.

Schweiggert-Weisz, U., Eisner, P., Bader-Mittermaier, S., & Osen, R. (2020). Food proteins from plants and fungi. *Current Opinion in Food Science, 32*, 156–162.

Shams-White, M. M., Chung, M., Du, M., Fu, Z., Insogna, K. L., Karlsen, M. C., et al. (2017). Dietary protein and bone health: A systematic review and meta-analysis from the National Osteoporosis Foundation. *The American Journal of Clinical Nutrition, 105*(6), 1528–1543.

Smetana, S., Aganovic, K., Irmscher, S., & Heinz, V. (2018). Agri-food waste streams utilization for development of more sustainable food substitutes. In *Designing sustainable technologies, products and policies* (pp. 145–155). Springer.

Stojceska, V., Ainsworth, P., Plunkett, A., & İbanoǧlu, S. (2008). The recycling of brewer's processing by-product into ready-to-eat snacks using extrusion technology. *Journal of Cereal Science, 47*(3), 469–479.

Summer, A., Formaggioni, P., Franceschi, P., Di Frangia, F., Righi, F., & Malacarne, M. (2017). Cheese as functional food: The example of Parmigiano Reggiano and Grana Padano. *Food Technology and Biotechnology, 55*(3), 277–289.

Tian, S., Xu, Q., Jiang, R., Han, T., Sun, C., & Na, L. (2017). Dietary protein consumption and the risk of type 2 diabetes: A systematic review and meta-analysis of cohort studies. *Nutrients, 9*(9), 982.

Uddin, Z., Suppakul, P., & Boonsupthip, W. (2016). Effect of air temperature and velocity on moisture diffusivity in relation to physical and sensory quality of dried pumpkin seeds. *Drying Technology, 34*(12), 1423–1433.

Usman, I. (2011). *Assessing the water footprint of tofu produced from organically cultivated crops*.

van Gastelen, S., Dijkstra, J., & Bannink, A. (2019). Are dietary strategies to mitigate enteric methane emission equally effective across dairy cattle, beef cattle, and sheep? *Journal of Dairy Science, 102*(7), 6109–6130.

van Huis, A., & Oonincx, D. G. (2017). The environmental sustainability of insects as food and feed. A review. *Agronomy for Sustainable Development, 37*(5), 1–14.

van Lieshout, G. A., Lambers, T. T., Bragt, M. C., & Hettinga, K. A. (2020). How processing may affect milk protein digestion and overall physiological outcomes: A systematic review. *Critical Reviews in Food Science and Nutrition, 60*(14), 2422–2445.

van Lingen, H. J., Niu, M., Kebreab, E., Valadares Filho, S. C., Rooke, J. A., Duthie, C. A., et al. (2019). Prediction of enteric methane production, yield and intensity of beef cattle using an intercontinental database. *Agriculture, Ecosystems & Environment, 283*, 106575.

van Vliet, S., Burd, N. A., & van Loon, L. J. (2015). The skeletal muscle anabolic response to plant-versus animal-based protein consumption. *The Journal of Nutrition, 145*(9), 1981–1991.

Vanham, D., Mekonnen, M. M., & Hoekstra, A. Y. (2020). Treenuts and groundnuts in the EAT-Lancet reference diet: Concerns regarding sustainable water use. *Global Food Security, 24*, 100357.

Vasilaki, V., Katsou, E., Ponsá, S., & Colón, J. (2016). Water and carbon footprint of selected dairy products: A case study in Catalonia. *Journal of Cleaner Production, 139*, 504–516.

Vinayashree, S., & Vasu, P. (2021). Biochemical, nutritional and functional properties of protein isolate and fractions from pumpkin (*Cucurbita moschata var. Kashi Harit*) seeds. *Food Chemistry, 340*, 128177.

Vitali, A., Grossi, G., Martino, G., Bernabucci, U., Nardone, A., & Lacetera, N. (2018). Carbon footprint of organic beef meat from farm to fork: A case study of short supply chain. *Journal of the Science of Food and Agriculture, 98*(14), 5518–5524.

Volpe, R., Messineo, S., Volpe, M., & Messineo, A. (2015). Carbon footprint of tree nuts based consumer products. *Sustainability, 7*(11), 14917–14934.

Wang, X., Warkentin, T. D., Briggs, C. J., Oomah, B. D., Campbell, C. G., & Woods, S. (1998). Trypsin inhibitor activity in field pea (Pisum sativum L.) and grass pea (Lathyrus sativus L.). *Journal of Agricultural and Food Chemistry, 46*(7), 2620–2623.

Wang, Y., Tibbetts, S. M., Berrue, F., McGinn, P. J., MacQuarrie, S. P., Puttaswamy, A., et al. (2020). A rat study to evaluate the protein quality of three green microalgal species and the impact of mechanical cell wall disruption. *Foods, 9*(11), 1531.

Wu, G. (2016). Dietary protein intake and human health. *Food & function, 7*(3), 1251–1265.

Yahoo Finance. (2021). *Sophie's bionutrients develops world's first dairy-free micro-algae based milk alternative*. URL: https://au.finance.yahoo.com/news/sophies-bionutrients-develops-worlds-first-102500607.html. Accessed 2021, August 4.

Yimenu, S. M., Kim, J. Y., & Kim, B. S. (2017). Prediction of egg freshness during storage using electronic nose. *Poultry Science, 96*(10), 3733–3746.

Zeece, M. (2020). Chapter nine – Food systems and future directions. In *Introduction to the chemistry of food* (pp. 345–397). Academic Press.

Zhuang, H., & Savage, E. M. (2010). Comparisons of sensory descriptive flavor and texture profiles of cooked broiler breast fillets categorized by raw meat color lightness values1. *Poultry science, 89*(5), 1049–1055.

5 Lipids

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Abstract

Fats are not all bad. In fact, we need them for energy, to absorb fat soluble vitamins and to grow healthy body and brain. Saturated lipids should be consumed in moderation to prevent cardiovascular disease, considering the length of their fatty acid chain: the shorter the better. This applies to health effects and footprint, with short chain saturated fats being predominant in plants. Unsaturated lipids mostly come from seeds and nuts, with vast differences in water and carbon footprint, taste and price. Again, they are not all the same. Finally, omega-3 fatty acids are important for human health. Fish is rich in docosahexanoic (DHA) and eicosapentaenoic (EPA), particularly bioactive, but intensive fishing may pose environmental issues. Some plant sources are more sustainable (seeds) but less abundant in DHA and EPA or too expensive (algae). Recent innovations offer interesting solutions by enhancing taste and availability (price) of sustainable solutions for lipids.

Keywords

Dairy · Footprint · Lipids · Nuts · Omega-3 · Seeds

5.1 Lipids for Human Nutrition

Lipids are an essential macronutrients in human diet. Their key feature is the ability to dissolve in non-polar solvents, such as oil. There are many types of lipids. Biochemically, dietary lipids can be: fatty acids, glycerolipids, glycerophospholipids, sphingolipids, sterols, prenols, saccharolipids, and polyketides (Fahy et al., 2005). Nutritionally, an important classification separates fatty acids into short chain (5 or less carbons), medium chain (6–12 carbons) and long chain (13 or more carbons). Based on their degree of saturation, they are further separated into saturated (no double bonds) and unsaturated (1 or more double bonds), with the latter further separated into monounsaturated (1 double bond), polyunsaturated (2 or more double bonds). Particular attention is given to the location of the double bonds, categorizing fatty acids as omega-3 (ω-3), omega-6 (ω-6) and omega-9 (ω-9) (Koliaki et al., 2019; Leray, 2014).

This nutritional nomenclature reflects lipids impact on human health. Lipids provide the most energy among all nutrients: 9 kcal/g vs. 4 kcal/g of carbohydrates and protein. In addition, they exert several bioactivities: store energy in the

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body, regulate hormonal activity, transmit nervous messages, protect organs such as the brain, and carry fat-soluble vitamins (A, D, E, K) (Leray, 2014). Nonetheless, excessive lipid consumption results in negative consequences such as cardiovascular diseases, affecting blood vessels (thrombosis), hearth (heart dysfunctions) and brain (stroke) (Koliaki et al., 2019; Leray, 2014). In addition, lipids modulate gut microbiome (the bacteria found in human intestine) by either promoting or inhibiting specific bacteria, resulting in either positive or negative effects on human health (Schoeler & Caesar, 2019). It is noteworthy that some fatty acids in the human body are not from dietary lipids, but rather the result of microbial fermentation of dietary fibre. Short chain fatty acids such as acetic acid, butyric acid and propionic acid support the growth of health-promoting (probiotic) bacteria (Schoeler & Caesar, 2019). Lipids are digested via inclusion in lipoproteins. Based on the amount and type of lipids ingested, these structures can be high density (more protein, HDL) or low density (LDL). A high ratio of HDL over LDL is preferred for cardiovascular health since they better flow in the bloodstream (Koliaki et al., 2019; Leray, 2014).

Saturated lipids such as stearic acid (C18:0) are present mostly in animal foods such as beef, dairy and eggs, and some plants (palm and coconut kernels). They have come under scrutiny for their negative impact on cardiovascular health. Recent studies have pointed a crucial difference in health effects based on their chain length. Dietary intake of medium chain saturated fatty acids (common in foods like coconut) resulted in higher levels of high density lipoprotein (HDL) than that of long chain saturated fatty acids (common in foods like meat and dairy) (Panth et al., 2018). These findings suggest that both saturation and length must be considered, depicting positive health outcomes for medium chain saturated fatty acids.

Unsaturated lipids such as oleic acid (C18:1, n-9) are the preferred choices and are abundant in plant-based foods (nuts, oily seeds, seaweeds) and specific animal-based foods (eggs, fish). On top of the well-known health properties, they also exert antimicrobial properties (Das, 2018). Among unsaturated fats, omega-3 fatty acids such as α-linoleic acid (C18:1, n-3) are present in seafood and few nuts and seeds. They protect against inflammations, cardiovascular diseases and cancer (Saini & Keum, 2018).

The effect of lipids on human health is wide. Let's take as example "Lorenzo's oil", a combination of different triglycerides that was formulated to slow the effects of a degenerative neural disease called adrenoleukodystrophy or ALD. The two main compounds are erucic acid and oleic acid, major constituents of rapeseed oil and olive oil, respectively (Kaplan et al., 1993). These two dietary lipids significantly improved patient's conditions. Even though Lorenzo's oil does not reverse the illness, it does show the effect that diet can have on human health. In fact, polar lipids, such as phosphatidyletanolamine and sphingomyelin have been shown to support brain health (Schverer et al., 2020).

Therefore, this book chapter presents and discuss traditional and innovative sources of lipids. Lipids have been classified into saturated, unsaturated and omega-3 fatty acids, to offer the reader with a comprehensive view (nutrition, sustainability, acceptability) of food sources for each of these nutrients. An example of the modern trajectory of lipid-rich food products is depicted in Fig. 5.1–5.3).

5.2 Traditional Food Sources of Lipids

5.2.1 Saturated Lipids

Saturated lipids are mostly found in animal foods, so butter and beef steak were chosen as representatives of dairy and meat. Nonetheless, plant-based ingredients such as coconut and palm oil score higher in saturated lipids, so coconut oil was chosen as example (Table 5.1). Coconut oil is almost entirely constituted by saturated lipids, 82.5 g/100 g (USDA, 2019), of medium chain. The main fatty acid is lauric acid which only contains 12 carbons (Wallace, 2019). Growing coconut requires medium levels of water, arguably less than other nuts: 4490 vs. 16,095 L/kg for coconut and almonds, respectively (Mekonnen & Hoekstra, 2011). Carbon footprint is low: only

Fig. 5.1 Representative sources of saturated lipids: traditional (butter) and innovative (blend of coconut oil and sunflower oil)

Fig. 5.2 Representative sources of unsaturated lipids: traditional (almonds) and innovative (avocado oil)

1.8 kg CO_2/kg coconut oil (Shonnard et al., 2015), minimising its environmental impact. This ingredient is very popular due to its ability to be solid at room temperature and dissolve in the mouth, providing a creamy texture and nutty, slightly acidic taste (Villarino et al., 2007). A similar but ingredient, palm oil, has received negative feedback from consumers. It is widely used by the food industry due to its low cost: 0.7 vs. 1.1–1.7 NZD/100 g (Countdown, 2021; Trading Economics, 2021). Nonetheless, it requires large volumes of land and produces far more carbon emissions: 2.2–8.0 vs. 1.8 kg CO_2/kg oil in comparison to coconut oil (Shonnard et al., 2015). The large number, 8.0, accounts for land use in palm harvesting due to deforestation of tropical land. Therefore, coconut oil seems to be a more sustainable source of plant-based saturated lipids.

Looking at animal foods, the stark differences lay in the lipid profile, being longer chain: palmitic (C16:0) and stearic acid (C18:0) being the predominant types (Hwang & Joo, 2017; Pustjens et al., 2017). This is correlated with higher LDL cholesterol, negatively associated with cardiovas-

Fig. 5.3 Representative sources of omega-3 fatty acids: traditional (flaxseeds) and innovative (hemp seeds, chia seeds)

Table 5.1 Representative food sources of lipids: products, nutritional value (quantity, quality), sustainability (water footprint, price), and acceptability

	Nutrition		Sustainability		Acceptability	
Food products	Lipid quantity (g/100 g)	Major fatty acids (% and structure)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory profile
Saturated lipids						
Coconut oil	82.5 USDA (2019)	42% lauric (C12:0), 17% myristic (C14:0) Wallace (2019)	4,490 Mekonnen and Hoekstra (2011)	1.8 Shonnard et al. (2015)	1.1–1.7 Countdown (2021)	Colourless, slightly acidic, sweet, salty, nutty Villarino et al. (2007)
Butter	45.6 USDA (2019)	28% palmitic (C16:0), 12% stearic (C18:0) Pustjens et al. (2017)	5,553 Hoekstra (2012)	9–15 Flysjö (2011)	1.1–2.4 Countdown (2021)	Creamy, melt in mouth, salty, sweet O'Callaghan et al. (2016)
Beef	11.4 USDA (2019)	26% palmitic (C16:0), 9% stearic (C18:0) Hwang and Joo (2017)	15,415 Hoekstra (2012)	20–43 Ruviaro et al. (2015)	2.4–3.2 Countdown (2021)	Tender, bloody, brown, umami Legako et al. (2016)
Unsaturated lipids						
Olive oil, extra virgin	78.3 USDA (2019)	72% oleic (C18:1), 10% linoleic (C18:2) Gurdeniz et al. (2010)	14,431 Mekonnen and Hoekstra (2011)	4.4–10.1 Pattara et al. (2016)	1.4–2.3 Countdown (2021)	Fruity, bitter, pungent Lauri et al. (2013)
Almonds, roasted	48.7 USDA (2019)	66% oleic (C18:1), 25% linoleic (C18:2) Čolić et al. (2017)	16,095 Mekonnen and Hoekstra (2011)	2.6 Volpe et al. (2015)	2.7–3.3 Countdown (2021)	Sweet, roasted, nutty, hard Lipan et al. (2020)

(continued)

Table 5.1 (continued)

	Nutrition		Sustainability		Acceptability	
Food products	Lipid quantity (g/100 g)	Major fatty acids (% and structure)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory profile
Sesame seeds	40.6 Elleuch et al. (2011)	43% oleic (C18:1), 41% linoleic (C18:2) Tenyang et al. (2017)	9,371 Mekonnen and Hoekstra (2011)	3.7 Sah and Devakumar (2018)	1.0–1.5 Countdown (2021)	Paste: white, sesame aroma, fluid Hou et al. (2018)
Omega-3 fatty acids						
Flaxseeds	13.8 NIH (2021)	38–46% α-linolenic (C18:3.ω-3) Teneva et al. (2014)	5,168 Mekonnen and Hoekstra (2011)	0.46 Jaiswal and Agrawal (2020)	0.8–1.1 Countdown (2021)	Flour: dark, viscous, grainy, oxidized Zhu and Li (2019)
Walnuts	5.4–10 Zwarts et al. (1999)	8–15% α-linolenic (C18:3,ω-3) Zwarts et al. (1999)	9,280 Mekonnen and Hoekstra (2011)	1.29 Marvinney et al. (2014)	2.2–3.6 Countdown (2021)	Nutty, oily, floral, sweet Miller et al. (2013)
Salmon, smoked	0.95–1.6 Jensen et al. (2012)	8–12% Docosahexanoic (C22:6,ω-3), 6–7% eicosapentaenoic (C22:5,ω-3), 1–3% α-linolenic (C18:3.ω-3) Jensen et al. (2012)	1,950 Hognes et al. (2014)	6.5 Ziegler et al. (2021)	7.2–9.0 Countdown (2021)	Pink, smoky, salty, amine odour Cardinal et al. (2004)

cular health (Panth et al., 2018). Furthermore, more water is required to produce red meat (up to 15,425 L/kg) (Hoekstra, 2012) and drastically more carbon is emitted in the atmosphere: up to 15 and 43 kg CO_2/kg of butter and beef, respectively (Flysjö, 2011; Ruviaro et al., 2015). The only positive factor for these foods is taste (creamy, umami) (O'Callaghan et al., 2016) and the lower fat content (46 g/100 g in butter and 11 g/100 g in steak) (USDA, 2019).

5.2.2 Unsaturated Lipids

Unsaturated lipids are mostly found in oily fruits, nuts and seeds. The first difference that comes to attention is the fatty acid profile. While fruits mostly contain oleic acid (C18:1), nuts and seeds contain more of its polyunsaturated form linoleic acid (C18:2), with the highest linoleic content in seeds (Čolić et al., 2017; Gurdeniz et al., 2010; Tenyang et al., 2017). Monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA) are metabolised differently, with the latter being more prone to being used as source of energy due to the presence of more double bonds. MUFA are less likely to oxidise in lipoproteins, while PUFA lower the amount of LDL cholesterol (DiNicolantonio & O'Keefe, 2017; Polley et al., 2018). Therefore, a healthy diet requires both MUFA and PUFA.

Environmentally, seeds require less water, although still being demanding: about 10,000 vs. about 15,000 L/kg (Mekonnen & Hoekstra, 2011) due to plant requirement (fruits, nuts, seeds) and processing requirement (oil production). The amount of carbon produced is moderate and so is the price, with almonds releasing about 3 kg CO_2/kg product. Sustainability-wise, sesame seeds seem slightly better, but not by much. Thus, price and personal taste preference may play a role.

5.2.3 Omega-3 Fatty Acids

Sources of omega-3 fatty acids span from seeds (chia, flax) to nuts (walnuts) and seafood (salmon, seaweeds). Plants offer extremely large amounts of these nutrients: 5–14 g/100 g vs. only 0.95–1.6 g/100 g of salmon (Jensen et al., 2012; NIH, 2021; Zwarts et al., 1999). Nonetheless, it is not the same nutrient. While plants only contain α-linolenic acid (C18:3, ω-3) (ALA), fish also contains docosahexanoic acid (C22:6, ω-3) (DHA) and eicosapentaenoic acid (C22:5, w-5) (EPA) (Jensen et al., 2012; Teneva et al., 2014; Zwarts et al., 1999). Nutritionally, each one of these 3 main omega-3 exerts different bioactivities: ALA effectively lowers LDL cholesterol, DHA and EPA enhance the synthesis of tissue factor pathway inhibitor, an anticoagulant protein (Goyens & Mensink, 2006). The ALA can be partially converted into DHA and EPA by the human body but with low efficiency. It is therefore important to include a variety of foods in our diet. Fatty fish and seaweeds are the main source of DHA and EPA (Jensen et al., 2012; Schmid et al., 2018). Thus, inclusion of seafood in the diet is recommended, keeping in mind carbon emissions. While salmon production produces about 6.5 kg CO_2/kg smoked salmon, seaweeds have the extraordinary ability to sequester atmospheric carbon (Leong et al., 2021), thus resulting in a negative carbon balance, making them an excellent sustainable choice of omega-3 fatty acids.

Environmentally, flaxseeds have lower impact than other options, along with the abovementioned seaweeds. Both of these foods are used as ingredients and/or condiments in bakery products (seeds), soups and sushi (seaweeds). Every source of omega-3 fatty acids faces the challenge of being prone to oxidation, with consequent “fishy” smell. Seeds and nuts are darker and nuttier, while smoked salmon scores much higher in terms of appreciation, being pink, smoky and salty (Cardinal et al., 2004). Unfortunately, it is also the most expensive food: 7.2–9.0 vs 0.8–3.6 NZD/100 g (Countdown, 2021). Thus, environmental concerns and price limit the appeal of fish, while sensory is the main challenge for plant-based options.

5.3 Innovative Food Sources of Lipids

5.3.1 Saturated Lipids

Given the lower footprint of coconut production, as opposed to palm oil, meat and dairy, the market of coconut-based foods has grown steadily, at an estimated 7% CAGR (compound annual growth rate) in 2021–2026 (MarketWatch, 2021). This trend produced vegetable spreads, yoghurt and ice cream that carry 54, 23 and 7.4 g saturated fats/100 g, respectively (Duck Island, 2021; Feliz Whole Foods, 2021; Pato et al., 2021; Raglan, 2021; Soler, 2005). Coconut yoghurt and ice cream are mainly a source of medium chain saturated fat C12 (lauric acid). Interestingly, the spread is a combination of coconut and sunflower oil (Feliz Whole Foods, 2021). The combination of saturated and unsaturated vegetable oils is becoming common in the food industry. One of the reasons is the different melting point (high for coconut, low for sunflower) which allows for highly acceptable sensory quality: creamy, mouth-melting and coating (Sura et al., 2020). This type of product results in high acceptability, while presenting moderate environmental impact. Nutritionally, this integration results in less lauric acid (saturated) and more oleic acid (unsaturated) offering a more comprehensive lipid profile due to the inclusion of sunflower oil (Onemli, 2012). Yoghurt and ice cream from coconut received high acceptability from plant-based consumers, while still rating lower than dairy in terms of taste and creaminess (Dong et al., 2021; Grasso et al., 2020).

5.3.2 Unsaturated Lipids

Modern sources of lipids, their bioavailability and footprint are presented in Table 5.2. Just like for traditional sources, unsaturated lipids are found in fruits, nuts and seeds. What changes is processing and, sometimes, the raw material itself. For example, while olive oil is a well-established staple food, particularly in the Mediterranean cuisine, avocado oil is an emerging condiment, with an estimated 5.9% CAGR in

Table 5.2 Innovative food sources of lipids: raw materials, bioavailability (fatty acid profile) and sustainability (water and carbon footprint)

Products	Raw materials	Bioavailability	Sustainability	
		Fatty acid profile (Quantity, % total lipid)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)
Saturated lipids				
Coconut/sunflower spread	Coconut, sunflower seeds	54 g/100 g Feliz Whole Foods (2021)	4,490 (seeds) Mekonnen and Hoekstra (2011)	1.8 Shonnard et al. (2015)
Coconut yoghurt	Coconut	23 g/100 g 51% Lauric (C12:0), 9.6% Myristic (C14:0) Pato et al. (2021) and Raglan (2021)		
Coconut ice cream	Coconut	7.4 g/100 g 50% Lauric (C12:0) Duck Island (2021) and Soler (2005)		
Unsaturated lipids				
Avocado oil	Avocado	78 g/100 g 56–68% oleic (C18:1), 10–19% linoleic (C18:2) Green and Wang (2020) and Olivado (2021)	1,981 (avocado) Mekonnen and Hoekstra (2011)	1.4 Hadjian et al. (2019)
Cashew butter	Cashew nuts	34 g/100 g 62% oleic (C18:1), 19% linoleic (C18:2) Ghazzawi and Al-Ismail (2017) and Pic's (2021)	14,218 (cashew nuts) Mekonnen and Hoekstra (2011)	2.2 Agyemang et al. (2016)
Sunflower butter	Sunflower seeds	48 g/100 g 44–74% linoleic (C18:2), 14–43% oleic (C18:1) Akkaya (2018) and Ceres (2021a, b)	3,366 (sunflower seeds) Mekonnen and Hoekstra (2011)	0.88 Yousefi et al. (2017)
Omega-3 fatty acids				
Hemp seeds oil	Hemp seeds	19 g/100 ml 16–19% α-linolenic (C18:3.ω-3) Babiker et al. (2021), Ceres (2021a, b), and Hemp Farm (2021)	3,685 (hemp) Mekonnen and Hoekstra (2011)	0.68 Campiglia et al. (2020)
Duckweed (water lentils, lentein)	*Lemnaceae*	1.7–2.4 g/100 g 33–48% α-linolenic (C18:3.ω-3) Appenroth et al. (2017) and Parabel (2021)	Not available, 98% water recyclable Parabel (2021)	−3.0 Mohedano et al. (2019)
Chia drink	Chia seeds	0.8 g/100 ml 52–69% α-linolenic (C18:3.ω-3) Chia Sisters (2021) and De Falco et al. (2017)	Not available	1.2 Jay (2015)

the 2021–2026 timeframe (360ResearchReports, 2020). This was likely due to the popularity of avocado as fruit. Its composition is comparable to that of olive oil, with a majority of oleic acid, followed by linoleic (Green & Wang, 2020; Olivado, 2021). Avocados require slightly less water than olives to grow (1,981 vs. 3,015 L/kg) (Mekonnen & Hoekstra, 2011) but these numbers must be put in context. Olive trees require moderate irrigation and grow in temperature climates (Berenguer et al., 2006). Avocado trees require less water when grown in tropical conditions. Nonetheless, avocado popularity has led to the incorporation of this fruit in the farms of several countries of various climates (Central America, South America, East Africa, South East Asia, Oceania). Thus, the actual footprint might be higher based on geographical location (Sommaruga & Eldridge, 2020). The carbon footprint is comparable to that of olive oil, but it could become greater when considering transportation. Consequently, growing locally is a better option when the climate allows (subtropical, warm and humid with limited to no frost). What differentiates these two sources of oil is sensory. While avocado oil resemble olive one in dark green colour, aroma and taste are different, described as grassy and vinegar (Hausch et al., 2020) thus limiting its consumer acceptance. In addition, extra virgin avocado oil is very expensive, as much as 2–3 times more than extra virgin olive oil (Countdown, 2021), likely due to the limited supply chain and manufacturing facilities established for this new product.

Spreads from nuts and seeds are far more successful in terms of consumer acceptance. Building on the popularity of peanut butter, manufacturers broadened the product range to almond butter, cashew butter, macadamia butter and even sunflower butter. The idea is offering a high oil spread (about 50% oil) with protein, fibre and other nutrients, while delivering new flavours. Compared to peanut butter, the composition is similar, with more linoleic acid: 44–74 g/100 g in sunflower spread vs. 27 g/100 g (Akkaya, 2018; Özcan & Seven, 2003). Environmentally, seeds seem to be a better option, requiring as far as 5 times less water than nuts to be produced and with less than half of carbon emissions (Agyemang et al., 2016; Mekonnen & Hoekstra, 2011; Yousefi et al., 2017). Nonetheless, prices are very high (Countdown, 2021), possibly because of their novelty and limited supply, limiting their applications in human diet. Nonetheless, it opens the door to new ingredients.

5.3.3 Omega-3 Fatty Acids

Innovation is strong in the area of omega-3 fatty acids. Apart from the well-known sources of fish, walnuts and flaxseeds, new seeds and seafood have arisen. Chia seeds offer similar nutritional benefits as flaxseeds (De Falco et al., 2017; Teneva et al., 2014) with comparable sensory profile (Jay, 2015; Zhu & Li, 2019). Therefore, a beverage made out of chia seeds and fruit juice results in a smooth, viscous texture, where the flavour is impacted mostly buy the fruits rather than the seeds themselves.

In 2018, hemp seeds have been legislated as safe for human consumption in most countries and markets (North and South America, European Union, Oceania) with restrictions mostly in Africa (Feldmann et al., 2020). This change addressed the fact that hemp seeds from food-grade cultivars contain little to no tetrahydrocannabinol (THC), which is the compound responsible for the psychoactive effects of hemp. Legal limits for THC concentrations are in place, such as 10 mg/kg seeds in New Zealand (MPI, 2020). Hemp seeds oil has quickly become popular, reaching CAGR of 18.5% for the USA alone, in the 2020–2030 decade (Future Market Insights, 2021). The nutritional potential is great, delivering as much as 19 g/100 ml of omega-3 fatty acids (Babiker et al., 2021; Ceres, 2021a, b; Hemp Farm, 2021). To put it in perspective, this is more than flaxseeds, which contains 14 g/100 g (NIH, 2021). Similarly to other plants, ALA is the only omega-3 fatty acid present. The environmental impact is just as interesting: moderate water consumption and very low carbon emissions (0.68 kg CO_2/kg hemp seeds) characterize hemp harvesting (Campiglia et al., 2020; Mekonnen & Hoekstra, 2011). The omega-6 to omega-3 ratio is 3:1, which is well-balanced nutritionally, while sensory might be a challenge due to the grassy, bitter aftertaste inherent to raw hemp seeds phenolics (Leonard et al., 2020). Further development in food technology should aim at improving the sensory quality of this ingredient while retaining its large nutritional potential for sustainable nutrition.

The biggest potential in the area of new sources of omega-3 fatty acids is seafood. While the concept of seafood typically refers to oceans, lakes and rivers, it can also be extended to ponds. Free-floating plants occur on the surface of still waters, such as ponds. Duckweed, also known as water lentil, due to its shape, is an example of such plant. Recent demands for sustainable nutrition have highlighted the potential of duckweed to deliver numerous nutrients, including omega-3 fatty acids (Bog et al., 2019). In 100 g of duckweed (wet weight) about 1.7–2.4 g are represented by the omega-3 fatty acid ALA, covering up to half of the lipid profile (Appenroth et al., 2017). The outstanding advantage of embracing duckweed as food is the environmental benefit. Not impact, but benefit. Being a water plant it is hard to quantify the water footprint. A food company claims that 98% of the water used to grow duckweed can be recycled (Parabel, 2021). This is possible, due to the ability of this plant to filter water. In fact, it is more commonly known for wastewater treatment (Li et al., 2020). Duckweed plant absorbs nitrogen, phosphorous and carbon from water and fixes it in its tissues to build protein and starch (Chen et al., 2018). This means that duckweed effectively removes nitrogen and carbon from water. This ability has been used to purify eutrophic water (polluted water such as waste streams from food processing or farming) (Chen et al., 2018; Li et al., 2020). A specific study quantified the amount of carbon sequestered and emitted by duckweed plants, balancing fixation and emissions. The result was that duckweed can fix up to 3 times the amount of CO_2 that it produces (Mohedano et al., 2019). Therefore, the carbon footprint of this plant is negative: −3.0 kg CO_2 produced per kg plant. This is an exciting result, showing the nutrition can sometimes be achieved without contributing to emissions but, in fact, reducing them. Obviously, this number does not account for food processing. Duckweed is typically harvested and dried prior to sales. Nonetheless, the possibility is there.

A special mention must be given to seaweed. Traditional ingredients in Asian cuisines, seaweeds contain lipids and omega-3 fatty acids. Unlike other plants, seaweed contain all the three main types of omega-3 fatty acids: ALA, DHA and EPA (Schmid et al., 2018). This gives them a more complete profile when compared to other plant foods, while causing less environmental impact than fish. In fact, seaweeds can sequester carbon from the ocean and fix it into their tissues, mostly to build fibre (Leong et al., 2021). Once again, plants with the ability to grow and thrive in water can deliver high quality lipids with benefits for the environment. The challenges lay in the handling of this plant material (collection, drying, storage), considering that they contain 80–90% water (El-Said & El-Sikaily, 2013) and the sensory quality (fishy, bitter, salty taste) (Stévant et al., 2020).

5.3.3.1 Omega-3 Fatty Acids and Covid-19

One interesting piece of information worth presenting is the role of polyunsaturated fatty acids (PUFA), and particularly omega-3 fatty acids, in the prevention and treatment of Covid-19 illness. Numerous recent studies have investigated this relationships, generating interesting information, worth studying further (Doaei et al., 2021; Goc et al., 2021; Hathaway III et al., 2020).

One study observed that PUFA can selectively bind to ACE2 (Angiotensin Converting Enzyme 2), which is the receptor for the Covid-19 virus, also known as SARS-CoV-2 (Goc et al., 2021). Therefore, PUFA limit the probability of this virus to successfully infect the host. Specifically, omega-3 fatty acids ALA, EPA and DHA (commonly found in seafood) and linoleic acid (animal and plant sources) can bind to this receptor, with EPA and DHA more successful than the others in doing so (Goc et al., 2021).

Similarly, another study showed that EPA and DHA are protective of cardiovascular diseases at blood concentrations of approximately 8%, while a values below 4% have been associated to higher mortality risk by cardiovascular disease. These nutrients have been suggested to lessen the complications of Covid-19 symptoms as result of a reduction in inflammation biomarkers (Hathaway III et al., 2020).

An *in vivo* study on Covid-19 patients documented a significantly higher survival rate after 1 month in those who were administered a diet rich in polyunsaturated fatty acids: 21% vs. 3% survival rate in the PUFA and control group, respectively. This study focused again on EPA and DHA (in a 2:1 ratio) (Doaei et al., 2021).

Finally, when talking about disease prevention and management, nutrition and lifestyle must be considered altogether. In the case of supporting immune health, the following advice has been given (Minich & Hanaway, 2020):

- Nutrition
  - Eat fruit, vegetables, fibre-rich foods, probiotic fermented foods
  - Avoid highly processed and refined food products rich in salt, sugar, saturated fats and with high glycemic index
- Lifestyle
  - Have a good sleep (6–8 h)
  - Exercise
  - Socialise and surround yourself with positive people and emotions.

These results by no mean represent medical advice, but they do offer insights on how nutrition and lifestyle can significantly effect human health. When choosing food we are choosing how to take care of ourselves.

5.4 Conclusions

This chapter has shown the vast number of dietary sources of lipids. Animal-based foods mostly supply saturated fats with long chain, while specific nuts (coconut, palm) provide medium chain saturated fats. Unsaturated fats can be found in seafood (fish, seaweed), oily fruits, nuts and seeds. Omega-3 fatty acids are more abundant in plants, but often limited to ALA (with the exception of seaweeds) while animal sources like salmon and other fatty fish deliver ALA, DHA and EPA. The environmental impact ranges from moderate to high for most of these sources, particularly for highly acceptable flavours (butter, beef, salmon, olive oil, almonds). Recent innovation have shifted the attention to spreads made with coconut oil, seeds and nuts, particularly effective in offering taste and sustainability when blended together. Lastly, aquaculture has shown enormous potential to produce sustainable nutrition. Plants like duckweed (water lentils) and algae like seaweeds contain a wide array of omega-3 fatty acids while sequestering carbon from the environment. Their carbon footprint is actually negative. This leaves room to the food industry to manufacture them into palatable food products (cooked, dried or other forms) with minimal impact.

References

360 Research Reports. (2020). https://www.360researchreports.com/global-avocado-oil-sales-market-16690782. Accessed on 16 Aug 2021.

Agyemang, M., Zhu, Q., & Tian, Y. (2016). Analysis of opportunities for greenhouse emission reduction in the global supply chains of cashew industry in West Africa. *Journal of Cleaner Production, 115*, 149–161.

Akkaya, M. R. (2018). Prediction of fatty acid composition of sunflower seeds by near-infrared reflectance spectroscopy. *Journal of Food Science and Technology, 55*(6), 2318–2325.

Appenroth, K. J., Sree, K. S., Böhm, V., Hammann, S., Vetter, W., Leiterer, M., & Jahreis, G. (2017). Nutritional value of duckweeds (*Lemnaceae*) as human food. *Food Chemistry, 217*, 266–273.

Babiker, E. E., Uslu, N., Al Juhaimi, F., Ahmed, I. A. M., Ghafoor, K., Özcan, M. M., & Almusallam, I. A. (2021). Effect of roasting on antioxidative properties, polyphenol profile and fatty acids composition of hemp (*Cannabis sativa L.*) seeds. *LWT, 139*, 110537.

Berenguer, M. J., Vossen, P. M., Grattan, S. R., Connell, J. H., & Polito, V. S. (2006). Tree irrigation levels for optimum chemical and sensory properties of olive oil. *HortScience, 41*(2), 427–432.

Bog, M., Appenroth, K. J., & Sree, K. S. (2019). Duckweed (Lemnaceae): Its molecular taxonomy. *Frontiers in Sustainable Food Systems, 3*, 117.

Campiglia, E., Gobbi, L., Marucci, A., Rapa, M., Ruggieri, R., & Vinci, G. (2020). Hemp seed production: Environmental impacts of Cannabis sativa L. agronomic practices by life cycle assessment (LCA) and carbon footprint methodologies. *Sustainability, 12*(16), 6570.

Cardinal, M., Gunnlaugsdottir, H., Bjoernevik, M., Ouisse, A., Vallet, J. L., & Leroi, F. (2004). Sensory characteristics of coldsmoked Atlantic salmon (*Salmo salar*) from European market and relationships with chemical, physical and microbiological measurements. Food Research International, 37(2), 181–193.

Ceres. (2021a). https://ceres.co.nz/products/grocery/ceres-organics/nut-seed-butters/organic-sunflower-butter/. Accessed on 11 Aug 2021.

Ceres. (2021b). https://shop.ceres.co.nz/Cooking/Condiments-and-Preserves/Oils/13010-Good-Hemp-Extra-Virgin-Hemp-Seed-Oil-500ml/. Accessed on 11 Aug 2021.

Chen, G., Fang, Y., Huang, J., Zhao, Y., Li, Q., Lai, F., et al. (2018). Duckweed systems for eutrophic water purification through converting wastewater nutrients

to high-starch biomass: Comparative evaluation of three different genera (*Spirodela polyrhiza, Lemna minor* and *Landoltia punctata*) in monoculture or polyculture. *RSC Advances, 8*(32), 17927–17937.
Chia Sisters. (2021). https://www.chia.co.nz/collections/chia/products/the-chia-mix. Accessed on 11 Aug 2021.
Čolić, S. D., Akšić, M. M. F., Lazarević, K. B., Zec, G. N., Gašić, U. M., Zagorac, D. Č. D., & Natić, M. M. (2017). Fatty acid and phenolic profiles of almond grown in Serbia. *Food Chemistry, 234*, 455–463.
Countdown. (2021). https://shop.countdown.co.nz/. Accessed on 9 Aug 2021.
Das, U. N. (2018). Arachidonic acid and other unsaturated fatty acids and some of their metabolites function as endogenous antimicrobial molecules: A review. *Journal of Advanced Research, 11*, 57–66.
De Falco, B., Amato, M., & Lanzotti, V. (2017). Chia seeds products: An overview. *Phytochemistry Reviews, 16*(4), 745–760.
DiNicolantonio, J. J., & O'Keefe, J. H. (2017). Good fats versus bad fats: A comparison of fatty acids in the promotion of insulin resistance, inflammation, and obesity. *Missouri Medicine, 114*(4), 303.
Doaei, S., Gholami, S., Rastgoo, S., Gholamalizadeh, M., Bourbour, F., Bagheri, S. E., et al. (2021). The effect of omega-3 fatty acid supplementation on clinical and biochemical parameters of critically ill patients with COVID-19: A randomized clinical trial. *Journal of Translational Medicine, 19*(1), 1–9.
Dong, Y., Sharma, C., Mehta, A., & Torrico, D. D. (2021). Application of augmented reality in the sensory evaluation of yogurts. *Fermentation, 7*(3), 147.
Duck Island. (2021). https://www.duckislandicecream.co.nz/. Accessed on 11 Aug 2021.
El-Said, G. F., & El-Sikaily, A. (2013). Chemical composition of some seaweed from Mediterranean Sea coast, Egypt. *Environmental Monitoring and Assessment, 185*(7), 6089–6099.
Elleuch, M., Bedigian, D., & Zitoun, A. (2011). Sesame (Sesamum indicum L.) seeds in food, nutrition, and health. In *Nuts and seeds in health and disease prevention* (pp. 1029–1036). Academic.
Fahy, E., Subramaniam, S., Brown, H. A., Glass, C. K., Merrill, A. H., Murphy, R. C., et al. (2005). A comprehensive classification system for lipids1. *Journal of Lipid Research, 46*(5), 839–861.
Feldmann, C., Follender, H., Armendariz, L., Cone, M., & Daly, K. (2020). The global commoditization of marijuana and hemp. *The Brief, 49*(4), 38–47.
Feliz Whole Foods. (2021). https://www.felizwholefoods.co.nz/our-products-1. Accessed on 11 Aug 2021.
Flysjö, A. (2011). Potential for improving the carbon footprint of butter and blend products. *Journal of Dairy Science, 94*(12), 5833–5841.
Future Market Insights. (2021). https://www.futuremarketinsights.com/press-release/hemp-seed-oil-market. Accessed on 16 Aug 2021.
Ghazzawi, H. A., & Al-Ismail, K. (2017). A comprehensive study on the effect of roasting and frying on fatty acids profiles and antioxidant capacity of almonds, pine, cashew, and pistachio. *Journal of Food Quality, 2017*, 1–8.
Goc, A., Niedzwiecki, A., & Rath, M. (2021). Polyunsaturated ω-3 fatty acids inhibit ACE2-controlled SARS-CoV-2 binding and cellular entry. *Scientific Reports, 11*(1), 1–12.
Goyens, P. L. L., & Mensink, R. P. (2006). Effects of alpha-linolenic acid versus those of EPA/DHA on cardiovascular risk markers in healthy elderly subjects. *European Journal of Clinical Nutrition, 60*(8), 978–984.
Grasso, N., Alonso-Miravalles, L., & O'Mahony, J. A. (2020). Composition, physicochemical and sensorial properties of commercial plant-based yogurts. *Food, 9*(3), 252.
Green, H. S., & Wang, S. C. (2020). First report on quality and purity evaluations of avocado oil sold in the US. *Food Control, 116*, 107328.
Gurdeniz, G., Ozen, B., & Tokatli, F. (2010). Comparison of fatty acid profiles and mid-infrared spectral data for classification of olive oils. *European Journal of Lipid Science and Technology, 112*(2), 218–226.
Hadjian, P., Egle, J., & Griesshammer, R. (2019). Life cycle assessment of three tropical fruits (avocado, banana, pineapple). *Tropical and Subtropical Agroecosystems, 22*, 127–141.
Hathaway, D., III, Pandav, K., Patel, M., Riva-Moscoso, A., Singh, B. M., Patel, A., et al. (2020). Omega 3 fatty acids and COVID-19: A comprehensive review. *Infection & Chemotherapy, 52*(4), 478.
Hausch, B. J., Arpaia, M. L., Kawagoe, Z., Walse, S., & Obenland, D. (2020). Chemical characterization of two California-grown avocado varieties (*Persea americana Mill.*) over the harvest season with an emphasis on sensory-directed flavor analysis. *Journal of Agricultural and Food Chemistry, 68*(51), 15301–15310.
Hemp Farm. (2021). https://hempfarm.co.nz/shop/kiwi-hemp-seed-oil-250ml/?gclid=EAIaIQobChMIhruQ-Pan8gIVjgkrCh1-JA3fEAYYASABEgJ-LfD_BwE. Accessed on 11 Aug 2021.
Hoekstra, A. Y. (2012). The hidden water resource use behind meat and dairy. *Animal Frontiers, 2*(2), 3–8.
Hognes, E. S., Nilsson, K., Sund, V., & Ziegler, F. (2014). *LCA of Norwegian salmon production 2012*. SINTEF. https://sintef.brage.unit.no/sintef-xmlui/handle/11250/2458163. Accessed on 9 Aug 2021
Hou, L-.X, Li, C-C., Wang, X.-D. (2018). Physicochemical Rheological and Sensory Properties of Different Brands of Sesame Pastes. *Journal of Oleo Science 67*(10) 1291–1298. 10.5650/jos.ess18109 https://doi.org/10.5650/jos.ess18109
Hwang, Y. H., & Joo, S. T. (2017). Fatty acid profiles, meat quality, and sensory palatability of grain-fed and grass-fed beef from Hanwoo, American, and Australian crossbred cattle. *Korean Journal for Food Science of Animal Resources, 37*(2), 153.
Lauri, I., Pagano, B., Malmendal, A., Sacchi, R., Novellino, E., & Randazzo, A. (2013). Application of "magnetic tongue" to the sensory evaluation

of extra virgin olive oil. *Food Chemistry, 140*, 692–699. S0308814612017098 https://doi.org/10.1016/j.foodchem.2012.10.135

Jaiswal, B., & Agrawal, M. (2020). Carbon footprints of agriculture sector. Carbon Footprints, 81–99.

Jay, J. (2015). Chapter 2: Carbon footprints of foods. In *Foodprints. Understanding connections between food choices and our environment*. UCLA (University of California Los Angeles)

Jensen, I. J., Mæhre, H. K., Tømmerås, S., Eilertsen, K. E., Olsen, R. L., & Elvevoll, E. O. (2012). Farmed Atlantic salmon (*Salmo salar* L.) is a good source of long chain omega-3 fatty acids. *Nutrition Bulletin, 37*(1), 25–29.

Kaplan, P. W., Tusa, R. J., Shankroff, J., Heller, J., & Moser, H. W. (1993). Visual evoked potentials in adrenolukodystrophy: A trial with glycerol trioleate and Lorenzo oil. *Annals of Neurology: Official Journal of the American Neurological Association and the Child Neurology Society, 34*(2), 169–174.

Koliaki, C., Liatis, S., & Kokkinos, A. (2019). Obesity and cardiovascular disease: Revisiting an old relationship. *Metabolism, 92*, 98–107.

Legako, J. F., Dinh, T. T. N., Miller, M. F., Adhikari, K., Brooks, J. C. (2016). Consumer palatability scores sensory descriptive attributes and volatile compounds of grilled beef steaks from three USDA Quality Grades. *Meat Science* 11277–85 S0309174015301133 https://doi.org/10.1016/j.meatsci.2015.10.018

Leong, Y. K., Chew, K. W., Chen, W. H., Chang, J. S., & Show, P. L. (2021). Reuniting the biogeochemistry of algae for a low-carbon circular bioeconomy. *Trends in Plant Science, 26*(7), 729–740.

Leray, C. (2014). *Lipids: Nutrition and health*. CRC Press.

Leonard, W., Zhang, P., Ying, D., & Fang, Z. (2020). Hempseed in food industry: Nutritional value, health benefits, and industrial applications. *Comprehensive Reviews in Food Science and Food Safety, 19*(1), 282–308.

Li, X., Wu, S., Yang, C., & Zeng, G. (2020). Microalgal and duckweed based constructed wetlands for swine wastewater treatment: A review. *Bioresource Technology, 318, 123858*.

MarketWatch. (2021). https://www.marketwatch.com/press-release/coconut-market-size-is-estimated-to-grow-with-a-cagr-of-73-during-2021-2026-with-top-countries-data-2021-06-07. Accessed on 12 Aug 2021.

Marvinney, E., Kendall, A., & Brodt, S. (2014, October). A comparative assessment of greenhouse gas emissions in California almond, pistachio, and walnut production. In *Proceedings of the 9th international conference on life cycle assessment in the agri-food sector*, pp. 761–771.

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences, 15*(5), 1577–1600.

Minich, D. M., & Hanaway, P. J. (2020). The functional medicine approach to COVID-19: Nutrition and lifestyle practices for strengthening host defense. *Integrative Medicine: A Clinician's Journal, 19* (Suppl 1), 54.

Miller, A. E., & Chambers, D. H. (2013). Descriptive analysis of flavor characteristics for black walnut cultivars. *Journal of food science, 78*(6), S887–S893.

Mohedano, R. A., Tonon, G., Costa, R. H., Pelissari, C., & Belli Filho, P. (2019). Does duckweed ponds used for wastewater treatment emit or sequester greenhouse gases? *Science of the Total Environment, 691*, 1043–1050.

MPI. (2020). https://www.mpi.govt.nz/dmsdocument/31623/direct. Accessed on 16 Aug 2021.

NIH (2021). Omega-3 Fatty Acids. URL: https://ods.od.nih.gov/factsheets/Omega3FattyAcids-HealthProfessional/

O'Callaghan, T. F., Faulkner, H., McAuliffe, S., O'Sullivan, M. G., Hennessy, D., Dillon, P., ... & Ross, R. P. (2016). Quality characteristics, chemical composition, and sensory properties of butter from cows on pasture versus indoor feeding systems. Journal of Dairy Science, 99(12), 9441–9460.

Olivado. (2021). https://www.olivado.com/en-nz/product/avocado-oil-extra-virgin. Accessed on 11 Aug 2021.

Onemli, F. (2012). Impact of climate changes and correlations on oil fatty acids in sunflower. *Pakistan Journal of Agricultural Research, 49*(4), 455–458.

Özcan, M., & Seven, S. (2003). Physıcal and chemıcal analysıs and fatty acıd composıtıon of peanut, peanut oıl and peanut butter from ÇOM and NC-7 cultıvars. *Grasas y Aceites, 54*(1), 12–18.

Panth, N., Abbott, K. A., Dias, C. B., Wynne, K., & Garg, M. L. (2018). Differential effects of medium-and long-chain saturated fatty acids on blood lipid profile: A systematic review and meta-analysis. *The American Journal of Clinical Nutrition, 108*(4), 675–687.

Parabel. (2021). https://www.parabel.com/lentein/. Accessed on 11 Aug 2021.

Pato, U., Yusuf, Y., Panggabean, I. P., Handayani, N. P., & Kusuma, A. (2021). Viability of lactic acid bacteria, fatty acid profile and quality of cocoghurt made using local and commercial starters during fermentation. *International Journal of Agricultural Technology, 17*(3), 1001–1014.

Pattara, C., Salomone, R., & Cichelli, A. (2016). Carbon footprint of extra virgin olive oil: A comparative and driver analysis of different production processes in Centre Italy. *Journal of Cleaner Production, 127*, 533–547.

Pic's. (2021). https://www.picspeanutbutter.com/. Accessed on 11 Aug 2021.

Polley, K. R., Miller, M. K., Johnson, M., Vaughan, R., Paton, C. M., & Cooper, J. A. (2018). Metabolic responses to high-fat diets rich in MUFA v. PUFA. *British Journal of Nutrition, 120*(1), 13–22.

Pustjens, A. M., Boerrigter-Eenling, R., Koot, A. H., Rozijn, M., & Van Ruth, S. M. (2017). Characterization of retail conventional, organic, and grass full-fat butters by their fat contents, free fatty acid contents, and triglyceride and fatty acid profiling. *Food, 6*(4), 26.

Raglan. (2021). https://raglanfoodco.com/. Accessed on 11 Aug 2021.
Ruviaro, C. F., de Léis, C. M., Lampert, V. D. N., Barcellos, J. O. J., & Dewes, H. (2015). Carbon footprint in different beef production systems on a southern Brazilian farm: A case study. *Journal of Cleaner Production, 96*, 435–443.
Sah, D., & Devakumar, A. S. (2018). The carbon footprint of agricultural crop cultivation in India. *Carbon Management, 9*(3), 213–225.
Saini, R. K., & Keum, Y. S. (2018). Omega-3 and omega-6 polyunsaturated fatty acids: Dietary sources, metabolism, and significance—A review. *Life Sciences, 203*, 255–267.
Schmid, M., Kraft, L. G., van der Loos, L. M., Kraft, G. T., Virtue, P., Nichols, P. D., & Hurd, C. L. (2018). Southern Australian seaweeds: A promising resource for omega-3 fatty acids. *Food Chemistry, 265*, 70–77.
Schoeler, M., & Caesar, R. (2019). Dietary lipids, gut microbiota and lipid metabolism. *Reviews in Endocrine and Metabolic Disorders, 20*(4), 461–472.
Schverer, M., O'Mahony, S. M., O'Riordan, K. J., Donoso, F., Roy, B. L., Stanton, C., et al. (2020). Dietary phospholipids: Role in cognitive processes across the lifespan. *Neuroscience & Biobehavioral Reviews, 111*, 183–193.
Shonnard, D. R., Fogliatti, D. P., & Kalnes, T. N. (2015). Response to comment on "life cycle carbon footprint of linear alkylbenzenesulfonate from coconut oil, palm kernel oil, and petroleum-based paraffins". *ACS Sustainable Chemistry & Engineering, 3*(8), 1688–1689.
Soler, L. (2005). *Development of non-dairy frozen dessert containing soy protein and coconut milk*. Master thesis. LSU Digital Commons.
Sommaruga, R., & Eldridge, H. M. (2020). Avocado production: Water footprint and socio-economic implications. *EuroChoices, 20*(2), 48–53.
Stévant, P., Ólafsdóttir, A., Déléris, P., Dumay, J., Fleurence, J., Ingadóttir, B., et al. (2020). Semi-dry storage as a maturation process for improving the sensory characteristics of the edible red seaweed dulse (*Palmaria palmata*). *Algal Research, 51*, 102048.
Sura, M., Megavath, V. S., Mohammad, A. S., Pendyala, S., Kulkarni, M., Sreeyapureddy, A., & Kuthadi, S. (2020). Studies of the quality parameters of blended oils and sensory evaluation of gram flour products. *Grain & Oil Science and Technology, 3*(4), 138–145.
Teneva, O. T., Zlatanov, M. D., Antova, G. A., Angelova-Romova, M. Y., & Marcheva, M. P. (2014). Lipid composition of flaxseeds. *Bulgarian Chemical Communications, 46*(3), 465–472.
Tenyang, N., Ponka, R., Tiencheu, B., Djikeng, F. T., Azmeera, T., Karuna, M. S., et al. (2017). Effects of boiling and roasting on proximate composition, lipid oxidation, fatty acid profile and mineral content of two sesame varieties commercialized and consumed in Far-North Region of Cameroon. *Food Chemistry, 221*, 1308–1316.
Trading Economics. (2021). https://tradingeconomics.com/commodity/palm-oil. Accessed on 12 Aug 2021.
USDA. FoodData Central. (2019). https://fdc.nal.usda.gov/. Accessed on 6 Aug 2021.
Villarino, B. J., Dy, L. M., & Lizada, M. C. C. (2007). Descriptive sensory evaluation of virgin coconut oil and refined, bleached and deodorized coconut oil. *LWT-Food Science and Technology, 40*(2), 193–199.
Volpe, R., Messineo, S., Volpe, M., & Messineo, A. (2015). Carbon footprint of tree nuts based consumer products. *Sustainability, 7*(11), 14917–14934.
Wallace, T. C. (2019). Health effects of coconut oil—A narrative review of current evidence. *Journal of the American College of Nutrition, 38*(2), 97–107.
Yousefi, M., Khoramivafa, M., & Damghani, A. M. (2017). Water footprint and carbon footprint of the energy consumption in sunflower agroecosystems. *Environmental Science and Pollution Research, 24*(24), 19827–19834.
Ziegler, F., Jafarzadeh, S., Skontorp Hognes, E., & Winther, U. (2021). Greenhouse gas emissions of Norwegian seafoods: From comprehensive to simplified assessment. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.13150
Zhu, F., & Li, J. (2019). Physicochemical and sensory properties of fresh noodles fortified with ground linseed (*Linum usitatissimum*). *LWT, 101*, 847–853.
Zwarts, G. P., Savage, D. L., & McNeil, L. (1999). Fatty acid content of New Zealand-grown walnuts (Juglans regia L.). *International Journal of Food Sciences and Nutrition, 50*(3), 189–194.

6 Minerals

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Abstract

We need numerous minerals for several reasons: strong bones, healthy brain, immunity, metabolism, red blood cells, reproductive health and more. Some are needed in large daily amounts such as mg (electrolytes), others in lower amounts such as µg (trace minerals). Geography is key, since minerals are found in soil and water. Food sources can concentrate minerals differently. For example, potassium abounds in bananas, iodine in seafood, zinc in organ meat and hemp seeds. Quality is important too: calcium is found in dairy and leafy greens, iron is abundant in meat and lentils. What differs is their bioavailability due to antinutrients (plant) and other factors such as acidity (animal). Food processing can optimize absorption of such nutrients. Furthermore, overlooked sources such as defatted seeds and "ugly" produce are abundant in minerals. Modern innovations can enhance their appeal by developing new food products which combine nutrition, low footprint and affordable taste.

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Keywords

Calcium · Iron · Magnesium · Potassium · Sodium · Zinc

6.1 Minerals for Human Nutrition: Electrolytes and Trace Minerals

Minerals are inorganic material, found in soil and water. Chemically, they are elements, not to be confused with the other minerals: salts present in rocks and soil. In human nutrition, the word "minerals" is used to describe chemical elements that are essential for humans. We don't synthesize them, we need them from food. Minerals are found in water and soil. From these resources, animals and plants absorb minerals and store them in different amounts. Large differences in mineral amount are present based on geographical location. Therefore, specific regions of the world are more or less abundant in these nutrients. The human body specifically needs 16 minerals, which are therefore deemed as essential, classified in 2 main groups based on their recommended daily intake (RDI) macro-minerals and trace minerals (Gharibzahedi & Jafari, 2017).

Macro-minerals or Electrolytes (RDI above100 mg/day) include:

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– Calcium (Ca)
– Chloride (Cl)
– Magnesium (Mg)
– Phosphorous (P)
– Potassium (K)
– Sodium (Na)
– Sulfur (S).

Why do we need them? Well, several reasons. Calcium (Ca) strengthens bones and teeth, and supports the immune system, muscle contraction and the nervous system (Gharibzahedi & Jafari, 2017; Peacock, 2010). Chloride (Cl) is needed in the stomach to produce hydrochloric acid and start the digestion (Gharibzahedi & Jafari, 2017; Turck et al., 2019). Magnesium (Mg) supports protein synthesis as well as the immune system, muscular and nervous dynamics by activating vitamin D (Gharibzahedi & Jafari, 2017; Uwitonze & Razzaque, 2018). Phosphorous (P) exhibits similar bioactivities as magnesium and, in addition to that, it provides energy by being a structural component of the ATP molecules (Chen et al., 2017; Gharibzahedi & Jafari, 2017; Wilck et al., 2019). Potassium (K) is involved in the fluid balance, along with sodium (Na), thus supporting muscles and nerves and regulating blood pressure (Arnold et al., 2017; Gharibzahedi & Jafari, 2017). Sulfur (S) is involved in the protection against bacteria and toxins (Gharibzahedi & Jafari, 2017; Jonsson et al., 2019).

Trace minerals (RDI below100 mg/day) include:

– Chromium (Cr)
– Cobalt (Co)
– Copper (Cu)
– Fluoride (F)
– Iodine (I)
– Iron (Fe)
– Manganese (Mn)
– Molybdenum (Mo)
– Selenium (Se)
– Zinc (Zn).

Trace minerals are equally as important as electrolytes, despite being needed in lower amounts. Chromium (Cr) affects fat metabolism (synthesis of cholesterol and fatty acids) and carbohydrate metabolism (insulin activity) (Gharibzahedi & Jafari, 2017; Swaroop et al., 2019). Cobalt (Co) is the central element in Vitamin B12, essential for healthy red blood cells. Interestingly, excessive blood concentrations of cobalt (>300 μg/L) can be toxic (Gharibzahedi & Jafari, 2017; Leyssens et al., 2017). Copper (Cu) is a key element in a wide range of processes, such enzymes and immune system (Gharibzahedi & Jafari, 2017; Prohaska, 2011). Fluoride (F) is essential for bone and tooth health (Gharibzahedi & Jafari, 2017; Štepec & Ponikvar-Svet, 2019) whereas iodine guarantees thyroid health (Gharibzahedi & Jafari, 2017; Abel et al., 2018). Iron (Fe) is needed to synthesise red blood cells and provide energy, also as enzyme constituent (Gharibzahedi & Jafari, 2017; McClung, 2019). Manganese (Mn) is vital for brain health, while Molybdenum (Mo) and Selenium (Se) activate antioxidant enzymes (Balachandran et al., 2020; Gharibzahedi & Jafari, 2017; Stupin et al., 2017). Finally, Zinc (Zn) is crucial for the reproductive system as well as for immunity (Gharibzahedi & Jafari, 2017; Kerns et al., 2018).

It is important to clarify the concept of bioavailability. Eating food or drinking water that contains nutrients does not mean absorbing all of it. Only a percentage of dietary minerals reaches our bloodstream through intestinal absorption. This is due to several reasons: the structure of the minerals themselves, food matrix, as well as the presence of promoters of absorption (organic acids such as citric, malic and lactic acid, but also vitamin A and β-carotene) or inhibitors (phytic acid, fibre, lignin, oxalate, and sometimes interaction with other minerals). Lastly, the health status of the subject plays a role too (Affonfere et al., 2021). In this regard, processing can come to a help. Common technologies such as soaking, boiling, germination and fermentation can degrade inhibitors, thus enhancing bioavailability (Affonfere et al., 2021; Kumari & Platel, 2020).

Deficiencies in any of these nutrients can result in serious disease. Therefore, it is paramount to achieve enough of these minerals through nutrition. Doing so sustainably is a social responsibility and allows us to respect and promote local communities. This chapter provides a comprehensive discussion of the traditional and innovative food sources of a representative range of essential minerals. Differences in geographical locations will result in altered values of mineral concentration and food availability. Nonetheless, our scope is to provide the reader with the big picture on minerals: sources, bioavailability, sustainability and acceptability. An example of the modern trajectory of mineral-rich food products is depicted in Figs. 6.1–6.4.

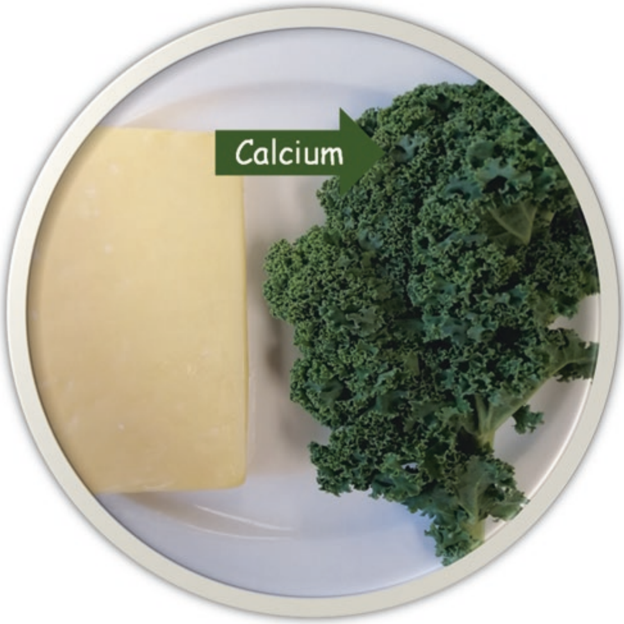

Fig. 6.1 Representative sources of Calcium: traditional (cows cheese) and innovative (kale)

Fig. 6.2 Representative sources of Magnesium: traditional (pumpkin seeds) and innovative (chia beverage)

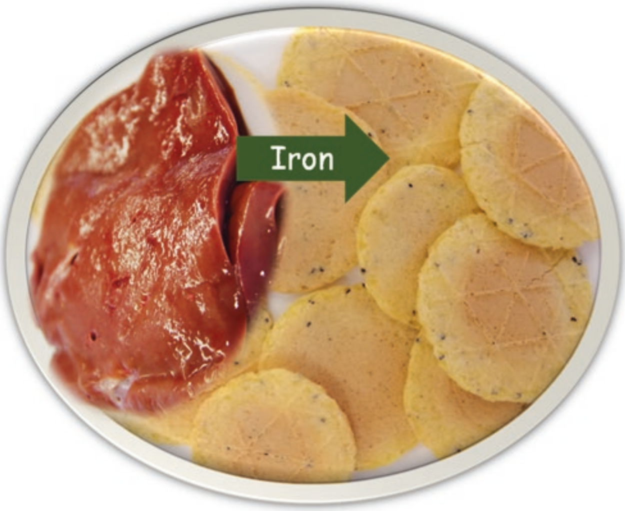

Fig. 6.3 Representative sources of Iron: traditional (liver) and innovative (chickpea crackers). (Image: https://wordpress.org/openverse/image/d7e13e1a-2ac7-449d-808d-676554cb411e (jlastras))

Fig. 6.4 Representative sources of Zinc: traditional (oysters) and innovative (hemp seeds)

6.2 Traditional Food Sources of Minerals

6.2.1 Electrolytes (Calcium, Magnesium, Potassium, Sodium)

As stated in Sect. 6.1, electrolytes are calcium, chloride, magnesium, phosphorous, potassium, sodium and sulfur. Phoshporous and sulfur are found in protein-rich foods. Sulfure, in particular, is found in 4 amino acids: methionine, cysteine, homocysteine, and taurine (Brosnan & Brosnan, 2006). Therefore, these electrolytes are considered in the discussion of protein (Chap. 5). Sodium and chloride are considered together, since they often appear in the same food sources such as salt. Calcium, magnesium and potassium complete this overview.

Calcium is needed for bone health, therefore recommended to prevent bone fractures. Comprehensive studies have documented dietary calcium intake (Balk et al., 2017) and incidence of hip fracture (Curtis et al., 2017), commonly associated to insufficient calcium status. The highest intake of calcium (>800 mg/day) was recorded in western and Nordic countries (North America, Europe, Scandinavia and Oceania) while low intakes (<500 mg/day) were found in South America and Asia, with limited information available from Africa. This was attributed to the higher consumption of milk and dairy products in western countries (Balk et al., 2017). Nonetheless, the world map of hip fracture revealed the exact opposite of what one might believe. The high calcium consuming regions showed higher prevalence of hip fractures (150–250 fractures/100,000 people) as opposed to the low calcium consuming regions (<150 fractures/100,000 people) (Curtis et al., 2017). Therefore, consuming calcium itself is not enough, absorption is key. Absorption of calcium is affected by diet and exercise. An interesting study compared 3 diets (animal-based, plant-based and mixed) showing that the mixed pattern correlated to higher bone density, a marker of bone health. This study reported the need for absorption promoters: fibre, potassium, retinol (mostly from plants) and Vitamin B12 (mostly from animals). These promoters enhance calcium absorption, contrasting the inhibitory effect of cholesterol, high protein, high fat (mostly from animals) and antinutrients (mostly from plants). This nutrient combination overlaps with that of the Mediterranean diet, rich in wholegrains, nuts, seeds and with low to moderate amounts of dairy and seafood (Melaku et al., 2017). Antioxidants were also found to be positively correlated with bone density (Kim et al., 2021). Finally, exercise has been shown to improve bone health. While walking merely limits bone mass loss, strengthening exercise (weight-lifting or movements that require muscle strength above that of a daily routine) and aerobic activities (running, biking) significantly increase bone density (Benedetti et al., 2018). Therefore, both diet and physical activity are key to healthy bones. Diet-wise, dairy represent the most abundant source of calcium. For example, cheddar cheese delivers 740 mg/100 g, covering 60–71% of the RID for women and men, respectively (NIH, 2021; USDA, 2019). Unfortunately, the environmental footprint of dairy is large, requiring 5,000–5,500 L water/kg cheddar cheese (Kumar & Joshiba, 2019), producing a whopping 14 kg CO_2/kg cheese (Gosalvitr et al., 2019). Its high popularity is due to the enticing taste, almost addicting (umami taste), described as sweet, bitter, creamy and milky (Zhao et al., 2019) (Table 6.1).

Magnesium, on the contrary, is found mainly in plant-based foods, with roasted pumpkin seeds being one of the major sources: on average, 100 g of pumpkin seeds deliver 153 mg of magnesium, which is 43–48% of the RDI (NIH, 2021). Environmentally very friendly, pumpkin production requires very little water (less than 100 L/kg) (Fandika et al., 2019) releasing as little as 0.1–0.2 kg CO_2/kg pumpkin (Schäfer & Blanke, 2012). These results are common for vegetables. The challenge here is sensory. It is much easier to eat 100 g of cheese than 100 g of roasted seeds since the latter taste nutty yes, but are also hard in texture (Uddin et al., 2016). Both cheese and pumpkin are relatively expensive, reaching 1.3 and 1.9 NZD/100 g for cheese and roasted pumpkin seeds, respectively (Countdown, 2021).

Far easier is the access to potassium, sodium and chloride. Potassium is found in moderate amounts (10–20% RDI) in fruits (dried fruits, fresh bananas and oranges), vegetables (pumpkins, potatoes), grains (legumes such as lentils) with lower amounts in dairy and meat (NIH, 2021). Of these, the most commonly consumed food is fruit, particularly bananas (Bolton et al., 2019), hence the choice for this discussion. There are numerous cultivars of bananas, with Cavendish being one of the most common. On average, 100 g of bananas guarantee about 358 mg of potassium (USDA, 2019), equal to 10% of the RDI (EFSA, 2019). They are tasty, sweet (Cano et al., 1997) and cheap, usually below 1 dollar per 100 g (Countdown, 2021). On top of that, banana production is environmentally friendly, requiring only 790 L water/kg product (Mekonnen & Hoekstra, 2011) and releasing

Table 6.1 Representative food sources of electrolytes: products, nutritional value (quantity, bioavailability), sustainability (water and carbon footprint) and acceptability (price, sensory)

	Nutrition		Sustainability		Acceptability	
Food products	Minerals quantity (mg/100 g)	Bioavailability (% RDI)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory profile
Calcium						
Cheddar cheese	714 USDA (2019)	60–71% (women, men) NIH (2021)	5,000–55,000 Kumar and Joshiba (2019)	14 Gosalvitr et al. (2019)	1.3 Countdown (2021)	Sweet, bitter, umami, milky, creamy Zhao et al. (2019)
Magnesium						
Roasted pumpkin seeds	153 NIH (2021)	43–48% NIH (2021)	82 Fandika et al. (2019)	0.1–0.2 Schäfer and Blanke (2012)	1.9 Countdown (2021)	Brown/green, hard, nutty Uddin et al. (2016)
Potassium						
Banana	358 USDA (2019)	10% EFSA (2019)	790 Mekonnen and Hoekstra (2011)	0.5–1.0 Iriarte et al. (2014)	0.8 Countdown (2021)	Pale yellow, firm, sweet Cano et al (1997)
Sodium, chloride						
Bread	406–455 Coyne et al. (2018)	20–23% EFSA (2019)	1,608 Mekonnen and Hoekstra (2011)	0.5 Ingrao et al. (2018)	0.3–0.4 Countdown (2021)	Porous appearance, floury, malty, buttery Heenan et al. (2008)

0.5–1.0 kg CO_2/kg product (Iriarte et al., 2014). Bananas grow in tropical weather, with abundance of rainfall and water. Their harvesting requires minimum amount of fertilizers, pesticides and post-harvest energy input (electricity, packaging) (Iriarte et al., 2014). The key issue here is transport. Bananas only grow in tropical regions, thus export to other parts of the world result in carbon footprint. This varies from country to country, but it can be quite high, resulting in double emissions, from 0.5 to 1.0 kg CO_2/kg bananas, as a consequence of the oil use for overseas transport (Iriarte et al., 2014). These factors ignited a debate on whether eating bananas in non-tropical countries is bad for the environment (Berners-Lee, 2020). As you can see from Table 6.1, the footprint numbers don't look bad, but minimising transportation of food can achieve both lower carbon emissions and higher quality (fresh food, can hardly be kept as such when shipped long distance, particularly true for perishable items such as produce). Therefore, alternatives to bananas based on local supply. Luckily, potassium is found in a variety of fruits, vegetables and grains, offering sustainable solutions: local sources of potassium with similar quantity and quality.

Sodium and chloride are both essential (we need them) and an element of concern (if consumed excessively). They also known as salt when combined into sodium chloride (NaCl), which is their main source. Salt is used in a variety of processed foods, with bread being the most common example. Typically, bread contains up to 1% of salt, that means anywhere from 406 to 455 mg of sodium/100 g bread (Coyne et al., 2018) which covers 20–23% of the RDI of 2,300 mg per day (EFSA, 2019). The RDI for chloride is 3,100 mg per day (Turck et al., 2019) and bread typically contains around 600 mg of chloride since salt is 60% chloride. Bread production is quite sustainable: requiring moderate amounts of water (1,608 L water/kg bread0 (Mekonnen & Hoekstra, 2011) and releasing as little as 0.5 kg CO_2/kg bread (Ingrao et al., 2018) due to its simple processing. Bread main ingredients is wheat flour and wheat is a highly productive crop. Breadmaking involves mixing, fermentation, baking and packaging, which can be carried out on a large scale, with low energy input and carbon emissions (Ingrao et al., 2018). Adding to this, bread can be cheap, as low in price as 0.3–0.4 NZD/100 g (Countdown, 2021) and very tasty, almost addicting, due to its fluffy, porous texture, malty taste and buttery texture (Heenan et al., 2008). It could almost be said that bread does too much of a good job in delivering chloride and sodium, with the risk of contributing to excess salt intake. To avoid this risk, foods that are highly processed should be avoided or limited, things like canned foods, preserved vegetables, ham, cheese, contain high levels of salt, thus caution must be paid if and when approaching such foods.

6.2.2 Trace Minerals (Copper, Iodine, Iron, Selenium, Zinc)

Trace minerals are chromium, cobalt, copper, fluoride, iodine, iron, manganese, molybdenum, selenium and zinc. Chromium is found in meat and grains, similarly to iron, which will be discussed in detail in this section. Cobalt is a key element in vitamin B12 so it will be included in Chap. 7 (water soluble vitamins). Fluoride is found in produce, grains and meat, depending on abundance in the soil. Manganese and molybdenum are found in wholegrains and seafood. Copper, iodine, iron (heme and non-heme), selenium and zinc are presented as case study for trace minerals (Table 6.2).

Copper is found in very high levels in beef liver and oyster, thus the latter was chosen as example. A 100 g serving of beef liver delivers as much as 15 mg/100 g of copper, meaning 16 times the RDI (NIH, 2021). This is due to the functionality of liver in ruminants, filtering food and stocking minerals. Therefore, little of this food is needed to supply adequate levels of copper. It is important to state that excessive consumption of copper leads to toxic reactions, particularly damaging to the human liver (Taylor et al., 2020). The highest tolerable intake of copper is listed by NIH as 10 mg day, equal to about 67 g of beef liver (NIH, 2021). Thus, the high copper content of beef liver can be seen as both positive and negative, based on the amount consumed. Moreover, this food comes with an environmental price of resources needed (up to 16,000 l water/kg beef) (Gerbens-Leenes et al., 2013) and emissions produced. Cows farming requires land, water, feed and results in emissions from both cows and farming equipment .The carbon footprint of beef ranges from 18 to 25 kg CO_2/kg beef, for conventional and organic farming, respectively (Buratti et al., 2017). Price is moderate at 1.8 ND/100 g (New Zealand Fresh, 2021) being an organ meat, but flavour is polarizing due to a strong smell and taste (Kolbábek et al., 2019) adding a sensory challenge to the nutritional and environmental one (Tables 6.3 and 6.4).

Iodine is an interesting microelement, in the sense that its significant food source is seafood, whether plant or animal (seaweed, fish). The term seaweeds encompasses numerous varieties of plants, which contain 1.6–2.2 mg/100 g of dry seaweeds (NIH, 2021; Teas et al., 2004), meaning 10 times more than what we need. Unlike beef liver (serving size 75 g), a serving size of dry seaweeds is around 10 g (NIH, 2021) thus resulting in 1–1.5 times the daily need. It could be said that one serving of seaweed a day covers the iodine need. Another exciting factor is the positive effect on water quality. Seaweeds are capable of sequestering more CO_2 than they emit, with the only process contributing to emissions in drying. The combination of these two factors is a negative carbon footprint, from −49 to −85 kg CO_2/kg seaweed (Thomas, 2021). This is huge potential. It is therefore important to tackle the two challenges of dry seaweeds: price and taste. Nori costs around 11 ND/100 g (Countdown,

Table 6.2 Representative food sources of trace minerals: products, nutritional value (quantity, bioavailability), sustainability (water and carbon footprint) and acceptability (price, sensory)

	Nutrition		Sustainability		Acceptability	
Food products	Minerals quantity (mg/100 g)	Bioavailability (% RDI)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory profile
Copper						
Beef liver	15 NIH (2021)	1,621% NIH (2021)	15,712 Gerbens-Leenes et al. (2013)	18–25 Buratti et al. (2017)	1.8 New Zealand Fresh (2021)	Brown, strong smell, salty, compact Kolbábek et al. (2019)
Iodine						
Dry seaweeds	1.6–2.2 NIH (2021); Teas et al. (2004)	1,127–1,550% NIH (2021)	Not available	−49/−85 Thomas (2021)	11 Countdown (2021)	Salty, sea aroma, crispy, umami Stévant et al. (2018)
Iron						
Heme						
Pork liver	23 USDA (2019)	129–290% (women, men) NIH (2021)	5,988 Mekonnen and Hoekstra (2011)	2.9–4.4 Vergé et al. (2016)	2.3 Countdown (2021)	Umami, hard, bitter Zamuz et al. (2019)
Oysters	9.4 NIH (2021)	52–118% (women, men) NIH (2021)	Not available	1.9 Tamburini et al. (2019)	4.7 Countdown (2021)	Marine odour, earthy, salty, firm, juicy, chewy Cochet et al (2015)
Non-Heme						
Hummus	2.4 Wallace et al. (2016)	13–30% (women, men) NIH (2021)	4,177 Mekonnen and Hoekstra (2011)	0.18 Saget et al. (2020)	1.6 Countdown (2021)	Palatable Reister and Leidy (2020)
Dark chocolate	12 USDA (2019)	67–150% (women, men) NIH (2021)	17,196 Mekonnen and Hoekstra (2011)	2.0–4.7 Pérez-Neira et al. (2020)	1.7 Countdown (2021)	Nutty, berry and coffee taste, grainy, hard De Pelsmaeker et al. (2019)
Selenium						
Canned tuna in vegetable oil	108 NIH (2021)	196% NIH (2021)	Not available	3.7–7.7 Avadí et al. (2015)	1.4 Countdown (2021)	Pink, fishy, salty, oily, mealy Caponio et al. (2010)
Zinc Oyster	87 NIH (2021)	792% NIH (2021)	Not available	1.9 Tamburini et al. (2019)	4.7 Countdown (2021)	Marine odour, earthy, salty, firm, juicy, chewy Cochet et al (2015)

Table 6.3 Innovative food sources of electrolytes: raw materials, bioavailability and sustainability (water and carbon footprint)

Products	Raw materials	Bioavailability	Sustainability	
		Mineral quantity (mg/100 g) and %RDI	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)
Calcium				
Kale	Kale	197 (16–20%) NIH (2021); Szutowska et al. (2020)	Not available	0.1–0.4 Yuttitham (2019)
Magnesium				
Chia beverage	Chia	295 (82–92%) (men, women) Chia Sisters (2021); NIH (2021)	Not available	Not available
Potassium				
Banana bites	Upcycled bananas	1,500 (43%) Barnana (2021), EFSA (2019)	790 Roibás et al. (2015)	0.5–1.0 Iriarte et al. (2014)
Sodium, chloride				
Kelp powder	Kelp	3,300 (165%) EFSA (2019), Pacific Harvest (2021)	Not available	−49/−85 Thomas (2021)

2021) meaning 1.1 NZD per serving. The smell is fishy and salty, which could deter many from eating it, while the umami flavour could enticing Stévant et al. (2018).

Iron is a major source of discussion since its deficiency can cause anemia, which is worryingly abundant in children (43% globally) and women in reproductive age (39% globally), mostly from Africa and Asia (Blanco-Rojo & Vaquero, 2019). Iron is present in two forms: heme and non-heme. Heme is the free form of iron and it is found only in animal food such as meat. Non-heme iron is the bound form, thus less bioavailable, found in plants (such as grains and leafy greens) and animals, requiring acidity to be released from its components (Blanco-Rojo & Vaquero, 2019).

An example of heme iron is pork liver. As stated above, animal liver can store numerous minerals and other nutrients, delivering on average 23 g iron per 100 g liver (USDA, 2019), which equals to 129% of the RDI for women and 290% of the RDI for mean (NIH, 2021). Women require more iron (18 vs. 8 mg/day) due to menstruation, reaching as high as 27 mg/day during pregnancy (NIH, 2021). Therefore, high quantities of bioavailable iron are crucial for their health. Pork liver can deliver to this need, with moderate footprint (higher than plants, lower than cows): about 6000 L water needed (Mekonnen & Hoekstra, 2011) and 2.9–4.4 kg CO_2 emitted (Vergé et al., 2016) per kg produced. The price is reasonable and sensory quality carries both the challenge of bitterness and the attractivity of umami (Zamuz et al., 2019). Seafood is another source of heme iron is seafood. Oysters are quite rich in iron, comparatively lower than pork liver (9.4 vs. 23 mg/100 g) and twice as expensive (4.7 vs 2.3 NZD/100 g) (Countdown, 2021). Interestingly, they are more environmentally friendly, emitting about half as much carbon dioxide (1.9 vs. 2.9–4.4 kg CO_2/kg product) due to oyster ability to absorb large quantities of carbon from the water (Tamburini et al., 2019).

Non-heme iron is commonly found in legumes and spinach, but not many people know that it is also found in chocolate. Among legumes, chickpeas are one of the highest sources of iron. They are often processed into hummus, which can deliver 2.4 mg/100 g (Wallace et al., 2016). It is obviously a moderate amount: 13–30% RDI

Table 6.4 Innovative food sources of trace minerals: raw materials, bioavailability and sustainability (water and carbon footprint)

Products	Raw materials	Bioavailability	Sustainability	
		Mineral quantity (mg/100 g) and %RDI	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)
Copper				
Defatted sunflower meal	Defatted sunflower seeds	3.0 (325%) Planetarians (2021)	1,356 Mekonnen and Hoekstra (2011)	3.8 (oil) Schmidt (2015)
Iodine				
Roasted nori	Seaweeds	1.6–2.2 (1127–1550%) Ceres Organics (2021); Teas et al. (2004); USDA (2019)	Not available	−49/−85 Thomas (2021)
Iron				
Heme				
Mussel powder	Mussels	11 (61–138%) (women, men) Nutri NZ (2021); Waitaki Biosciences (2019)	Not available	0.6 (mussels) Yaghubi et al. (2021)
Grass fed beef liver supplement	Beef	5.8 (12–27%) (women, men) Home Grown Primal (2021)	13,074 Rodrigues and Dziedzic (2021)	19–37 Yaghubi et al. (2021)
Non-Heme				
Chickpea crackers	Chickpeas	5.9 (33–74%) (women, men) Krippu (2021)	4,177 Mekonnen and Hoekstra (2011)	0.18 (chickpeas) Saget et al. (2020)
Chocolate energy bar	Cacao	11 (61–138%) (women, men) The Functional Chocolate Company (2021); USDA (2019)	17,196 Mekonnen and Hoekstra (2011)	2.0–4.7 Pérez-Neira et al. (2020)
Selenium				
Roasted Brazil nuts	Brazil nuts	0.7–3.0 (1272–5454%) Cardoso et al (2017); NIH (2021)	9,063 HEALabel (2021)	2.0 HEALabel (2021)
Zinc				
Hemp flour	Hemp seeds	5.4–6.7 (49–61%) Mihoc et al. (2012)	3,685 Mekonnen and Hoekstra (2011)	0.68 Campiglia et al (2020)

(NIH, 2021) so it has to be part of a varied diet to guarantee sufficient intakes. Bioavailability of non-heme iron is increased by acidity and vitamin C, which reverse the antinutrient effects of phytate and oxalate (He et al., 2019) thus the presence of lemon juice in hummus can enhance its nutritional relevance. On a positive note, chickpeas have marginal environmental impact, requiring about 4,000 L water and producing only 0.18 kg CO_2 (Mekonnen & Hoekstra, 2011; Saget et al., 2020), are cheap and with a pleasant taste (Reister & Leidy, 2020). Dark chocolate is a fascinating topic. Yes, it contains 12 mg/100 g of non-heme iron, sufficient for 2/3 of women RDI and more than enough for men (USDA, 2019; NIH, 2021) but at a cost. Cocoa farming, distribution and chocolate production require a lot of resources, consuming a staggering 17,000 L of water per kg of chocolate (Mekonnen & Hoekstra, 2011) while producing relevant levels of carbon: 2.0–4.7 kg CO_2 (Pérez-Neira et al., 2020).

The environmental implications of cocoa are various due to its limited geographical origins (Mediterranean and tropical climates). With countries within south America being large exporters of this product with the implication of a lower socioeconomic climate being involved with low consideration for ethical environmental principles with how the cocoa is produced. This has caused a large degree of environmental damage which makes cocoa a volatile product on its accountability for sustainable production, with a large degree of deforestation in South America being correlated to cocoa production. Due to it also being a product match is extremely hard to manage and produce correctly there is a large degree of management that has sought after the use of environment damaging artificial fertilizers which cause soil erosion (Confectionery News, 2015). It also takes 17,000 litres of water to produce one kilo of cocoa beans which is high in consideration to how much water is being used concerning fertilizer which is accountable for nitrate leeching which causes soil erosion (Mekonnen & Hoekstra, 2011).

Selenium is found in a variety of foods, particularly seafood such as fish (tuna, sardines, shrimps and others). Tuna canned in vegetable oil is a staple food in many diets, with 100 g of it delivering twice as much selenium as needed: 108 mg/100 g (NIH, 2021; NOH, 2021). Its fishy, salty and mealy flavour is praised by many (Caponio et al., 2010) and the price is reasonable. The carbon footprint is the only challenge: ranging from 3.7 to 7.7 kg CO_2/kg canned tuna based on the type of oil chosen, with olive oil carrying heavier carbon burden than vegetable oil (Avadí et al., 2015).

Zinc, finally, is found in seafood and meat, as well as grains and seeds. One source stands out, covering as much as 8 times the RDI: oysters (NIH, 2021). Oysters also present the big advantage of producing low to moderate impact, with a carbon footprint of 1.9 (Tamburini et al., 2019). As discussed for iron, oysters can sequester carbon from the ocean, thus minimizing the impact of fishing and food processing. Challenges mainly reside in the price and acquired taste: fishy aroma, firm and chewy texture (Cochet et al., 2015).

6.3 Innovative Food Sources of Minerals

6.3.1 Electrolytes (Calcium, Magnesium, Potassium, Sodium)

Innovation in the field of electrolytes explored plant-based and upcycled options, with a focus on sustainability. Calcium can be found in green leafy vegetables such as spinach and kale, consumed either fresh or juiced. Kale contains moderate amount of calcium: 16–20% of the RDI (NIH, 2021; Szutowska et al., 2020). Nonetheless, green leafy vegetables like kale and spinach contain oxalate, a phytochemical known to inhibit calcium absorption by binding to it causing its excretion, potentially leading to kidney stones (von Unruh et al., 2004). Nonetheless, bioavailability of calcium from kale is higher than dairy: 40 vs. 30% absorption of dietary calcium, respectively. This is due to the different effect of calcium inhibitors in dairy (phosphorus and sulfur-containing proteins) and calcium absorption enhancers (vitamin D) compared to vegetables (phytate, oxalate) (Melse-Boonstra, 2020). Generally speaking, vegetables contain less calcium than dairy (about 3 times less, per 100 g basis) with comparable or slightly higher calcium absorption (20–40%) (Melse-Boonstra, 2020). Therefore, a healthy diet should consist of different dietary sources of calcium to guarantee adequate intake. Environmentally, vegetables offer the advantage of emitting far less carbon, as little as 30 times less: 0.1–0.4 kg CO_2/kg (with a 1.8 value recorded in one case (Yuttitham, 2019) versus 14 kg CO_2/kg of cheddar cheese (Gosalvitr et al., 2019). Kale as an ingredient represent an alternative way to consume calcium, nutritionally comparable to dairy, environmentally less impactful.

Magnesium, on the other hand, can be found mostly in plant foods. The challenge stands in their sensory quality and price. While nuts taste good but are expensive, seeds are more affordable but not as enticing (Countdownm, 2021; Uddin et al., 2016). Luckily, seeds are versatile. Those rich in mucilage, such as basil, chia and flax seeds can enhance juiciness of bakery products and mouthfeel of beverages and yoghurt (Marand et al., 2020; Martínez-Padilla, 2021; Niknam et al., 2019). A very popular new product is chia beverage. This drink takes advantage of the mucilage (which is a type of soluble fibre) found in chia seeds, making the beverage more viscous without affecting taste. The result is a beverage with pleasant mouthfeel (more viscous than water, but less viscous than smoothies), with the nutritional potential of chia seeds, which also includes magnesium (Ullah et al., 2016). The company Chia Sisters sell a beverage made with hydrated chia seeds, apple and blackcurrant concentrates, plus blackcurrant flavour (Chia Sisters, 2021). A 100-ml serve of this drink contains 295 mg magnesium, which means 82–92% of the RDI (Chia Sisters, 2021; NIH, 2021). This is a superior magnesium profile when compared to the next best food option, roasted pumpkins, which only account for half the amount (43–48%) (NIH, 2021). That's why it is important to ask the next question: what is the environmental cost of chia seeds? To the best of our knowledge, no information is available on this topic. Thus, research is warranted to guarantee that this is a sustainable choice.

Potassium is found in a variety of foods, but it is still banana to dominate the scene. Produce has short shelf-life, thus upcycling by-products with appropriate technology can be a solution. Bananas are processed into shelf-stable products such as salty chips (similar to potato chips, where potatoes are replaced by bananas and plantains) and cookies (with banana puree as first ingredient, providing structure and taste) (Barnana, 2021). This is a case where processing has a positive impact, with banana chips containing 4 times more potassium than fresh bananas as result of their drying process (Barnana, 2021; EFSA, 2019). Because many bananas are rejected for export if they are not perfect in appearance, are worn out, or are overripe. Barnana dehydrates these bananas to prevent food waste on organic banana farms (Barnana, 2021).

Sodium and chloride are most commonly found in bread, but many options are available. Now, given seaweeds nutritional value and low footprint, what about seaweed-based foods as source of minerals. Kelp powder is obtained upon drying of kelp, a brown algae. A typical serving size of dry seaweed is 10 g, which translates into 16.5% of the RDI (EFSA, 2019; Pacific Harvest, 2021). Kelp is rich in minerals, including sodium, potassium, calcium and magnesium (Schiener et al., 2014) and its affordable price can make up for this defect to some extent (Perry et al., 2019). Therefore, as one of the most abundant electrolytes in kelp, sodium is easily absorbed and utilized by human body.

While this sodium content is comparable to that of 100 g of bread, the impact on the environment is far lower. Let's look at carbon: while breadmaking is nearly carbon neutral with 0.5 kg CO_2/kg bread (Ingrao et al., 2018) kelp powder production is actually carbon negative, as low as −49/−85 kg CO_2/kg dry seaweed (Thomas, 2021). It must be noted that is quite difficult to calculate exactly how much carbon is sequestered by algae in oceans and other water reservoirs, as opposed to calculations based on laboratory settings. Nonetheless, the scientific community agrees that algae absorb large quantities of carbon from the water, factually cleaning it (Krause-Jensen & Duarte, 2016). Kelp culture is considered to be the least harmful form to aquaculture and the marine environment. Moreover, kelp can provide a series of ecosystem services for a variety of marine environments. In the temperate zone of the northern hemisphere, the natural community of *Laminaria* plays a key role in the coastal ecosystem (Visch et al., 2020). They not only provide shelter for a variety of related marine life but also provide foraging and breeding places for them (Walls et al., 2017). Compared with the natural community of kelp, kelp farms had the least effect on dissolved inorganic nutrient concentration and benthic oxygen flux, because most kelp farms did not need additional nitrogen fertilizer (Visch et al., 2020).

6.3.2 Trace Minerals (Copper, Iodine, Iron, Selenium, Zinc)

A very interesting innovation in the field of copper is upcycled sunflower meal. The oil industry generates by-products such as defatted sunflower meal, which is abundant in fibre, protein and minerals. The company Planetarians (2021) estimates 3.0 mg of copper in 100 g of their flour, this means an astounding 325% of the RDI. The ability to absorb copper is directly related to the amount of ascorbic acid (vitamin C) which is contained within the food ingredient. This is due to ascorbic-binding to the site of the enzyme cytochrome *c* oxidase, which plays a critical role in cellular energy production (Milne & Omaye, 1980). This enzyme is responsible for the absorption of copper and can be rapidly blocked by the excess of vitamin C. It would be recommended for copper absorption for an individual with copper deficiency to eat copper-rich foods separately from vitamin C rich foods. Being a by-product means lower resources needed: the water footprint of defatted sunflower meal is only 1,356 L/kg, 3 times lower than that of sunflower seeds (3,366–3,410 L/kg) (Mekonnen & Hoekstra, 2011).

Iodine can be found in seafood, with roasted nori taking advantage of a growing market, whose CAGR is expected to reach 11% by 2027 (PR Newswire, 2021). A 10 g serve of roasted nori can provide excellent levels of iodine: 127–155% of the RDI (Ceres Organics, 2021; Teas et al., 2004; USDA, 2019). All of these while sequestering CO_2 from the ocean (Thomas, 2021).

Heme iron mostly comes from animal flesh. The meat industry has researched the areas of mussel powder and beef liver supplements to offer nutrition and taste. Green-Lipped mussel powder is freeze dried for enhanced shelf-life of this otherwise short-living food. Mussel powder provides a relevant 61–138% of the iron RDI for women and men in 100 g (Nutri NZ, 2021; Waitaki Biosciences, 2019) with a very low carbon footprint of 0.6 kg CO2/kg mussels, due to their ability to filter water (Yaghubi et al., 2021). Only the drying and packaging processes will add to the emissions. A land-based option is beef liver supplement. The beef liver is freeze dried to maintain the integrity of the vitamins and minerals that naturally occur in the raw ingredient naturally (Home Grown Primal, 2021). Nonetheless, the iron content is not particularly high (12–27% RDI) (Home Grown Primal, 2021). Environmentally, the cost of beef ingredients is still too high: 13,074 L water needed and 19–37 kg CO_2 emitted per kg (Rodrigues & Dziedzic, 2021; Yaghubi et al., 2021).

In the plant kingdom, non-heme iron can come from chickpeas. A new innovative product that uses chickpeas as a source of iron is Krippu's Bio chickpea crackers with rosemary. Chickpea flour is the main ingredient in this food product, sunflower seeds and herbs such as rosemary, thyme, oregano and Himalayan salt are also added. Chickpea flour is processed from freeze drying the chickpeas to form a powder. This is also an example of a value added product as the way the raw ingredient is process increases the value of the product. The amount of iron per 100 g of chickpeas is 33–77% (Krippu, 2021). With the advantage, in this case, of a low footprint, especially for carbon emissions. This makes chickpea crackers stand out over chocolate energy bars, which do contain more iron, but cost 4 more times in terms of water requirement and 10–25 times more in terms of carbon emissions (Mekonnen & Hoekstra, 2011; Pérez-Neira et al., 2020; Saget et al., 2020).

As for selenium, brazil nuts have gained much popularity in the recent years. Their nutty, pleasant taste combines with an astonishing selenium content: 1,272–5,454% of the RDI (Cardoso et al., 2017; NIH, 2021). Therefore, a small handful of these nuts would provide more than enough selenium. Limited information is available on the footprint, making it imperative to determine such values.

Zinc. A recently considered source of zinc is hemp flour. Given the recent changes in legislation, hemp seeds have been deemed safe and legal for human consumption in most countries, launching its market (fibre, flour, hearts, oil) with a CAGR of 34% until 2026 (Intrado, 2021). Hemp flour contains on average 50% of the RDI for zinc (Mihoc et al., 2012), which is very high for plant foods, but drastically lower than oysters (16 times less). What makes hemp flour interesting is how gentle it is on the environment. The amount of water needed to grow and harvest hemp seeds is moderate, 3,685 L/kg (Mekonnen & Hoekstra, 2011), but this plant can offer so many solutions: seeds, leaves and fiberous components have multiple applications in food and textiles. In addition, only 0.68 kg CO_2/kg hemp seeds are released (Campiglia et al., 2020), making this plant versatile and sustainable.

6.3.3 Aquafaba Powder

A honorable mention goes to Aquafaba powder. This ingredients is obtained from the boiling water of chickpeas, which is further packages as a liquid (Ingredion, 2021) or sold as a powder (Vör Foods, 2021). As much as one third of the powder is represented by minerals. The mineral profile of Aquafaba from chickpeas consisted of potassium, phosphorous, sulphur, magnesium, calcium, sodium, iron, zinc, manganese, copper and molybdenum (Damian et al., 2018; Serventi, 2020). The serving size is not established, but it is safe to consider it either 100 ml of liquid or 5 g of powder (the liquid is typically 5% solids) (Serventi, 2020). Therefore, Aquafaba can deliver the following mineral profile:

- Molybdenum (94% RDI)
- Copper (7–9% RDI, men, women)
- Manganese (5–6% RDI, women, men)
- Iron (3–7% RDI, women, men)
- Potassium (6% RDI).

It is interesting to note that another boiling water, that of soybeans, contains twice as much iron and potassium (Serventi et al., 2018; Serventi, 2020). Therefore, given the large volume of soybean processing (soymilk, tofu, tempeh, texturize proteins and many other food products) soy cooking water could be the next source of iron and potassium.

6.4 Conclusions

In closing, essential minerals can be found in a variety of foods, with large differences in terms of bioavailability, sustainability and acceptability. This chapter offered a representative range of dietary sources, traditional and innovative. Traditionally, electrolytes and minerals can be found in organ meats, fish, dairy, eggs, grains, seeds, nut, fruits and vegetables. Novel mineral-rich foods are either less known foods (such as Brazil nuts, hemp seeds flour) or upcycled ingredients (defatted sunflower meal, Aquafaba). It is interesting how the food matrix affects bioavailability. For example, vitamin C has been shown to reduce copper absorption (by binding to an absorption enzyme) whereas is increases the absorption of non-heme iron (by releasing it from phytates and other antinutrients). As for calcium, absorption is guaranteed by promoters (fibre, potassium, Vitamin A and Vitamin B12) and contrasted by inhibitors (cholesterol, high protein and saturated fats from animals and oxalate from plants). Therefore, adhering to a diverse diet is key for mineral nutrition, while opting for sustainable choices helps the environment, thus our community.

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References

Abel, M. H., Korevaar, T. I., Erlund, I., Villanger, G. D., Caspersen, I. H., Arohonka, P., et al. (2018). Iodine intake is associated with thyroid function in mild to moderately iodine deficient pregnant women. *Thyroid, 28*(10), 1359–1371.

Affonfere, M., Chadare, F. J., Fassinou, F. T. K., Linnemann, A. R., & Duodu, K. G. (2021). In-vitro digestibility methods and factors affecting minerals bioavailability: A review. *Food Reviews International, 1*, 1–29.

Arnold, R., Pianta, T. J., Pussell, B. A., Kirby, A., O'Brien, K., Sullivan, K., et al. (2017). Randomized, controlled trial of the effect of dietary potassium restriction on nerve function in CKD. *Clinical Journal of the American Society of Nephrology, 12*(10), 1569–1577.

Avadí, A., Bolaños, C., Sandoval, I., & Ycaza, C. (2015). Life cycle assessment of Ecuadorian processed tuna. *The International Journal of Life Cycle Assessment, 20*(10), 1415–1428.

Balachandran, R. C., Mukhopadhyay, S., McBride, D., Veevers, J., Harrison, F. E., Aschner, M., et al. (2020). Brain manganese and the balance between essential roles and neurotoxicity. *Journal of Biological Chemistry, 295*(19), 6312–6329.

Balk, E. M., Adam, G. P., Langberg, V. N., Earley, A., Clark, P., Ebeling, P. R., et al. (2017). Global dietary calcium intake among adults: a systematic review. *Osteoporosis International, 28*(12), 3315–3324.

Barnana. (2021). URL: https://barnana.com/collections/chewy-banana-bites/products/organic-original-chewy-banana-bites. Accessed 2021, August 20.

Benedetti, M. G., Furlini, G., Zati, A., & Letizia Mauro, G. (2018). The effectiveness of physical exercise on bone density in osteoporotic patients. *BioMed Research International, 2018*, 4840531.

Berners-Lee, M. (2020). *How bad are bananas?: The carbon footprint of everything*. Profile Books Ltd..

Blanco-Rojo, R., & Vaquero, M. P. (2019). Iron bioavailability from food fortification to precision nutrition. A review. *Innovative Food Science & Emerging Technologies, 51*, 126–138.

Bolton, K. A., Trieu, K., Woodward, M., Nowson, C., Webster, J., Dunford, E. K., et al. (2019). Dietary intake and sources of potassium in a cross-sectional study of Australian adults. *Nutrients, 11*(12), 2996.

Brosnan, J. T., & Brosnan, M. E. (2006). The sulfur-containing amino acids: An overview. *The Journal of Nutrition, 136*(6), 1636S–1640S.

Buratti, C., Fantozzi, F., Barbanera, M., Lascaro, E., Chiorri, M., & Cecchini, L. (2017). Carbon footprint of conventional and organic beef production systems: An Italian case study. *Science of the Total Environment, 576*, 129–137.

Cano, M. P., de Ancos, B., Matallana, M. C., Cámara, M., Reglero, G., & Tabera, J. (1997). Differences among Spanish and Latin-American banana cultivars: morphological, chemical and sensory characteristics. Food Chemistry, 59(3), 411–419.

Cardoso, B. R., Duarte, G. B. S., Reis, B. Z., & Cozzolino, S. M. (2017). Brazil nuts: Nutritional composition, health benefits and safety aspects. Food Research International, 100, 9–18.

Campiglia, E., Gobbi, L., Marucci, A., Rapa, M., Ruggieri, R., & Vinci, G. (2020). Hemp seed production: Environmental impacts of Cannabis sativa L. Agronomic practices by life cycle assessment (LCA) and carbon footprint methodologies. *Sustainability, 12*(16), 6570.

Caponio, F., Bilancia, M. T., Summo, C., Gomes, T., & Pasqualone, A. (2010). A survey of in-oil canned tuna quality by sensory analysis and the determination of the oxidative degradation of the liquid medium. *International Journal of Food Properties, 13*(4), 672–681.

Ceres Organics. (2021). URL: https://ceres.co.nz/products/grocery/ceres-organics/snack-foods/organic-roasted-seaweed-nori-snack/. Accessed 2021, August 25.

Chia Sisters. (2021). Accessed from https://www.chiasisters.co.nz/.

Chen, K., Jiang, W. D., Wu, P., Liu, Y., Kuang, S. Y., Tang, L., et al. (2017). Effect of dietary phosphorus deficiency on the growth, immune function and structural integrity of head kidney, spleen and skin in young grass carp (*Ctenopharyngodon idella*). *Fish & Shellfish Immunology, 63*, 103–126.

Cochet, M., Brown, M., Kube, P., Elliott, N., & Delahunty, C. (2015). Understanding the impact of growing conditions on oysters: a study of their sensory and biochemical characteristics. *Aquaculture Research, 46*(3), 637–646.

Confectionery News. (2015). URL: https://www.confectionerynews.com/Article/2015/04/29/What-is-the-environmental-impact-of-cocoa-production. Accessed 2021, September 3.

Countdown. (2021). URL: https://shop.countdown.co.nz/. Accessed 2021, August 19.

Coyne, K. J., Baldridge, A. S., Huffman, M. D., Jenner, K., Xavier, D., & Dunford, E. K. (2018). Differences in the sodium content of bread products in the USA and UK: Implications for policy. *Public Health Nutrition, 21*(3), 632–636.

Curtis, E. M., Moon, R. J., Harvey, N. C., & Cooper, C. (2017). Reprint of: The impact of fragility fracture and approaches to osteoporosis risk assessment worldwide. *International Journal of Orthopaedic and Trauma Nursing, 26*, 7–17.

Damian, J. J., Huo, S., & Serventi, L. (2018). Phytochemical content and emulsifying ability of pulses cooking water. *European Food Research and Technology, 244*(9), 1647–1655.

De Pelsmaeker, S., De Clercq, G., Gellynck, X., & Schouteten, J. J. (2019). Development of a sensory wheel and lexicon for chocolate. *Food Research International, 116*, 1183–1191.

EFSA. (2019). URL: https://www.efsa.europa.eu/en/efsa-journal/pub/5778. Accessed 2021, August 20.

Fandika, I. R., Kemp, P. D., Millner, J. P., & Horne, D. (2019). Water footprint differences of producing cultivars of selected crops in New Zealand. In *Irrigation in agroecosystems*. IntechOpen.

Gerbens-Leenes, P. W., Mekonnen, M. M., & Hoekstra, A. Y. (2013). The water footprint of poultry, pork and beef: A comparative study in different countries and production systems. *Water Resources and Industry, 1*, 25–36.

Gharibzahedi, S. M. T., & Jafari, S. M. (2017). The importance of minerals in human nutrition: Bioavailability, food fortification, processing effects and nanoencapsulation. *Trends in Food Science & Technology, 62*, 119–132.

Gosalvitr, P., Cuellar-Franca, R., Smith, R., & Azapagic, A. (2019). Energy demand and carbon footprint of cheddar cheese with energy recovery from cheese whey. *Energy Procedia, 161*, 10–16.

He, W., Li, X., Ding, K., Li, Y., & Li, W. (2019). Ascorbic acid can reverse the inhibition of phytic acid, sodium oxalate and sodium silicate on iron absorption in Caco-2 cells. *International Journal for Vitamin and Nutrition Research, 88*(1–2). https://doi.org/10.1024/0300-9831/a000503

HEALabel. (2021). URL: https://healabel.com/b--ingredients/brazil-nuts. Accessed 2021, August 26.

Heenan, S. P., Dufour, J. P., Hamid, N., Harvey, W., & Delahunty, C. M. (2008). The sensory quality of fresh bread: Descriptive attributes and consumer perceptions. *Food Research International, 41*(10), 989–997.

Home Grown Primal. (2021). *Grass fed beef liver supplements*. Home Grown Primal. URL: https://homegrownprimal.co.nz/products/grass-fed-beef-liver-supplements. Accessed 2021, August 25.

Ingrao, C., Licciardello, F., Pecorino, B., Muratore, G., Zerbo, A., & Messineo, A. (2018). Energy and environmental assessment of a traditional durum-wheat bread. *Journal of Cleaner Production, 171*, 1494–1509.

Ingredion. (2021). URL: https://www.ingredion.com/na/en-us/ingredient/evanesse-cb-6194-37606h00.html. Accessed 2021, September 2.

Intrado. (2021). URL: https://www.globenewswire.com/news-release/2021/04/08/2206841/0/en/Global-Research-Study-on-Industrial-Hemp-Market-Size-Will-Reach-36-Billion-at-34-CAGR-by-2026-Facts-Factors.html. Accessed 2021, September 2.

Iriarte, A., Almeida, M. G., & Villalobos, P. (2014). Carbon footprint of premium quality export bananas: Case study in Ecuador, the world's largest exporter. *Science of the Total Environment, 472*, 1082–1088.

Jonsson, W. O., Margolies, N. S., & Anthony, T. G. (2019). Dietary sulfur amino acid restriction and the integrated stress response: Mechanistic insights. *Nutrients, 11*(6), 1349.

Kerns, K., Zigo, M., & Sutovsky, P. (2018). Zinc: A necessary ion for mammalian sperm fertilization competency. *International Journal of Molecular Sciences, 19*(12), 4097.

Kim, D., Han, A., & Park, Y. (2021). Association of Dietary Total Antioxidant Capacity with bone mass and osteoporosis risk in Korean women: analysis of the *Korea National Health and nutrition examination survey 2008–2011*. *Nutrients, 13*(4), 1149.

Kolbábek, P., Maxová, P., Kourimská, L., Lukešová, D., & Kotrba, R. (2019). Sensory evaluation of liver/meat pâté made from fresh or frozen eland meat and beef. *Scientia Agriculturae Bohemica, 50*(2), 71–79.

Krause-Jensen, D., & Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience, 9*(10), 737–742.

Krippu. (2021). URL: https://www.krippu.com/produkts/nutritional-value-bio-rosemary/. Accessed 2021, August 25.

Kumar, P. S., & Joshiba, G. J. (2019). Water footprint of agricultural products. In *Environmental water footprints* (pp. 1–19). Springer.

Kumari, M., & Platel, K. (2020). Impact of soaking, germination, fermentation, and thermal processing on the bioaccessibility of trace minerals from food grains. *Journal of Food Processing and Preservation, 44*(10), e14752.

Leyssens, L., Vinck, B., Van Der Straeten, C., Wuyts, F., & Maes, L. (2017). Cobalt toxicity in humans—A review of the potential sources and systemic health effects. *Toxicology, 387*, 43–56.

Marand, M. A., Amjadi, S., Marand, M. A., Roufegarinejad, L., & Jafari, S. M. (2020). Fortification of yogurt with flaxseed powder and evaluation of its fatty acid profile, physicochemical, antioxidant, and sensory properties. *Powder Technology, 359*, 76–84.

Martínez-Padilla, L. P. (2021). Viscosity of chia seed water suspension using two mixers and two approaches. *Biosystems Engineering, 210*, 60–68.

McClung, J. P. (2019). Iron, zinc, and physical performance. *Biological Trace Element Research, 188*(1), 135–139.

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences, 15*(5), 1577–1600.

Melaku, Y. A., Gill, T. K., Taylor, A. W., Adams, R., & Shi, Z. (2017). Association between nutrient patterns and bone mineral density among ageing adults. *Clinical Nutrition ESPEN, 22*, 97–106.

Melse-Boonstra, A. (2020). Bioavailability of micronutrients from nutrient-dense whole foods: Zooming in on dairy, vegetables, and fruits. *Frontiers in Nutrition, 7*, 101.

Mihoc, M., Pop, G., Alexa, E., & Radulov, I. (2012). Nutritive quality of romanian hemp varieties (Cannabis sativa L.) with special focus on oil and metal contents of seeds. *Chemistry Central Journal, 6*(1), 1–12.

Milne, D. B., & Omaye, S. T. (1980). Effect of vitamin C on copper and iron metabolism in the Guinea pig. *International Journal for Vitamin and Nutrition Research. Internationale Zeitschrift fur Vitamin- und Ernahrungsforschung. Journal International de Vitaminologie et de Nutrition, 50*(3), 301–308.

New Zealand Fresh. (2021). URL: https://newzealandfresh.sg/products/frozen-beef-liver-1kg-pack. Accessed 2021, August 20.

NIH. National Institute of Health. (2021). Retrieved from https://ods.od.nih.gov/factsheets/list-all/.

Niknam, R., Ghanbarzadeh, B., Ayaseh, A., & Adun, P. (2019). Comprehensive study of intrinsic viscosity, steady and oscillatory shear rheology of Barhang seed hydrocolloid in aqueous dispersions. *Journal of Food Process Engineering, 42*(4), e13047.

Nutri NZ. (2021). *Green lipped mussel 19000*. Nutri NZ. URL: https://www.nutrinz.com/products/green-lipped-mussel-19-000-90-vegecaps.html?gclid=EAIaIQobChMIgKn1z-3t8AIVEhwrCh1TzgagEAAYAyAAEgIfH_D_BwE. Accessed 2021, August 20.

Pacific Harvest. (2021). URL: https://pacificharvest.co.nz/seaweed-seasonings/nz-sea-kelp/kelp-powder-45g/. Accessed 2021, August 20.

Peacock, M. (2010). Calcium metabolism in health and disease. *Clinical Journal of the American Society of Nephrology, 5*(Supplement 1), S23–S30.

Pérez-Neira, D., Copena, D., Armengot, L., & Simón, X. (2020). Transportation can cancel out the ecological advantages of producing organic cacao: The carbon footprint of the globalized agrifood system of ecuadorian chocolate. *Journal of Environmental Management, 276*, 111306.

Perry, J. J., Brodt, A., & Skonberg, D. I. (2019). Influence of dry salting on quality attributes of farmed kelp (*Alaria esculenta*) during long-term refrigerated storage. *LWT, 114*, 108362.

Planetarians. (2021). URL: https://static1.squarespace.com/static/591629a5e58c620d7152b065/t/5b6c6bd61ae6cf38b779844e/1533832204613/PLANETARIANS+product+deck.pdf. Accessed 2021, August 25.

PR Newswire. (2021). URL: https://www.prnewswire.com/news-releases/seaweed-snacks-market-size-worth-3-36-billion-by-2027%2D%2Dcagr-10-8-grand-view-research-inc-301207189.html. Accessed 2021, September 2.

Prohaska, J. R. (2011). Impact of copper limitation on expression and function of multicopper oxidases (ferroxidases). *Advances in Nutrition, 2*(2), 89–95.

Reister, E. J., & Leidy, H. J. (2020). An afternoon hummus snack affects diet quality, appetite, and glycemic control in healthy adults. *The Journal of Nutrition, 150*(8), 2214–2222.

Rodrigues, U. J., & Dziedzic, M. (2021). *The water footprint of beef cattle in the amazon region, Brazil* (p. 51). Ciência Rural.

Roibás, L., Elbehri, A., & Hospido, A. (2015). Evaluating the sustainability of Ecuadorian bananas: Carbon footprint, water usage and wealth distribution along the supply chain. *Sustainable Production and Consumption, 2*, 3–16.

Saget, S., Costa, M., Barilli, E., de Vasconcelos, M. W., Santos, C. S., Styles, D., & Williams, M. (2020). Substituting wheat with chickpea flour in pasta production delivers more nutrition at a lower environmental cost. *Sustainable Production and Consumption, 24*, 26–38.

Schäfer, F., & Blanke, M. (2012). Farming and marketing system affects carbon and water footprint–A case study using Hokaido pumpkin. *Journal of Cleaner Production, 28*, 113–119.

Schiener, P., Black, K. D., Stanley, M. S., & Green, D. H. (2014). The seasonal variation in the chemical composition of the kelp species *Laminaria digitata*, *Laminaria hyperborea*, *Saccharina latissima* and *Alaria esculenta*. *Journal of Applied Phycology, 27*(1), 363–373.

Schmidt, J. H. (2015). Life cycle assessment of five vegetable oils. *Journal of Cleaner Production, 87*, 130–138.

Serventi, L. (2020). Cooking water compositions. In *Upcycling legume water: from wastewater to food ingredients* (pp. 73–85). Springer.

Serventi, L., Wang, S., Zhu, J., Liu, S., & Fei, F. (2018). Cooking water of yellow soybeans as emulsifier in gluten-free crackers. *European Food Research and Technology, 244*(12), 2141–2148.

Štepec, D., & Ponikvar-Svet, M. (2019). Fluoride in human health and nutrition. *Acta Chimica Slovenica, 66*(2), 255–275.

Stévant, P., Indergård, E., Ólafsdóttir, A., Marfaing, H., Larssen, W. E., Fleurence, J., et al. (2018). Effects of drying on the nutrient content and physico-chemical and sensory characteristics of the edible kelp Saccharina latissima. *Journal of Applied Phycology, 30*(4), 2587–2599.

Stupin, A., Cosic, A., Novak, S., Vesel, M., Jukic, I., Popovic, B., et al. (2017). Reduced dietary selenium impairs vascular function by increasing oxidative stress in Sprague-Dawley rat aortas. *International Journal of Environmental Research and Public Health, 14*(6), 591.

Swaroop, A., Bagchi, M., Preuss, H. G., Zafra-Stone, S., Ahmad, T., & Bagchi, D. (2019). Benefits of chromium (III) complexes in animal and human health. In *The nutritional biochemistry of chromium (III)* (pp. 251–278). Elsevier.

Szutowska, J., Rybicka, I., Pawlak-Lemańska, K., & Gwiazdowska, D. (2020). Spontaneously fermented curly kale juice: Microbiological quality, nutritional composition, antioxidant, and antimicrobial properties. *Journal of Food Science, 85*(4), 1248–1255.

Tamburini, E., Fano, E. A., Castaldelli, G., & Turolla, E. (2019). Life cycle assessment of oyster farming in the Po delta, northern Italy. *Resources, 8*(4), 170.

Taylor, A. A., Tsuji, J. S., Garry, M. R., McArdle, M. E., Goodfellow, W. L., Adams, W. J., & Menzie, C. A. (2020). Critical review of exposure and effects: Implications for setting regulatory health criteria for ingested copper. *Environmental Management, 65*(1), 131–159.

Teas, J., Pino, S., Critchley, A., & Braverman, L. E. (2004). Variability of iodine content in common commercially available edible seaweeds. *Thyroid, 14*(10), 836–841.

The Functional Chocolate Company. (2021). URL: https://funcho.co/products/energy-chocolate. Accessed 2021, August 25.

Thomas, J. B. (2021). *Environmental impacts of seaweed cultivation: Kelp farming and preservation*. Burleigh Dodds Publishing.

Turck, D., Castenmiller, J., De Henauw, S., Hirsch-Ernst, K. I., Kearney, J., Knutsen, H. K., et al. (2019). Dietary reference values for chloride. *EFSA Journal, 17*(9), 5779.

Uddin, Z., Suppakul, P., & Boonsupthip, W. (2016). Effect of air temperature and velocity on moisture diffusivity in relation to physical and sensory quality of dried pumpkin seeds. *Drying Technology, 34*(12), 1423–1433.

Ullah, R., Nadeem, M., Khalique, A., Imran, M., Mehmood, S., Javid, A., & Hussain, J. (2016). Nutritional and therapeutic perspectives of Chia (*Salvia hispanica L.*): A review. *Journal of Food Science and Technology, 53*(4), 1750–1758.

USDA. (2019). URL: https://fdc.nal.usda.gov/. Accessed 2021, August 19.

Uwitonze, A. M., & Razzaque, M. S. (2018). Role of magnesium in vitamin D activation and function. *Journal of Osteopathic Medicine, 118*(3), 181–189.

Vergé, X., Maxime, D., Desjardins, R. L., & VanderZaag, A. C. (2016). Allocation factors and issues in agricultural carbon footprint: A case study of the Canadian pork industry. *Journal of Cleaner Production, 113*, 587–595.

Visch, W., Kononets, M., Hall, P. O., Nylund, G. M., & Pavia, H. (2020). Environmental impact of kelp (Saccharina latissima) aquaculture. *Marine Pollution Bulletin, 155*, 110962.

von Unruh, G. E., Voss, S., Sauerbruch, T., & Hesse, A. (2004). Dependence of oxalate absorption on the daily calcium intake. *Journal of the American Society of Nephrology, 15*(6), 1567–1573.

Vör Foods. (2021). URL: https://www.vorfoods.com/aquafaba. Accessed 2021, September 2.

Waitaki Biosciences. (2019). URL: https://www.waitakibio.com/products/brands/pernatec/. Accessed 2021, August 25.

Wallace, T. C., Murray, R., & Zelman, K. M. (2016). The nutritional value and health benefits of chickpeas and hummus. *Nutrients, 8*(12), 766.

Walls, A., Kennedy, R., Edwards, M., & Johnson, M. (2017). Impact of kelp cultivation on the Ecological Status of benthic habitats and Zostera marina seagrass biomass. *Marine Pollution Bulletin, 123*(1–2), 19–27.

Wilck, N., Balogh, A., Markó, L., Bartolomaeus, H., & Müller, D. N. (2019). The role of sodium in modulating immune cell function. *Nature Reviews Nephrology, 15*(9), 546–558.

Yaghubi, E., Carboni, S., Snipe, R. M., Shaw, C. S., Fyfe, J. J., Smith, C. M., et al. (2021). Farmed mussels: a nutritive protein source, rich in omega-3 fatty acids, with a low environmental footprint. *Nutrients, 13*(4), 1124.

Yuttitham, M. (2019). Comparison of carbon footprint of organic and conventional farming of Chinese Kale. *Environment and Natural Resources Journal, 17*(1), 78–92.

Zamuz, S., Purriños, L., Galvez, F., Zdolec, N., Muchenje, V., Barba, F. J., & Lorenzo, J. M. (2019). Influence of the addition of different origin sources of protein on meat products sensory acceptance. *Journal of Food Processing and Preservation, 43*(5), e13940.

Zhao, X., Zheng, Z., Zhang, J., Sarwar, A., Aziz, T., & Yang, Z. (2019). Change of proteolysis and sensory profile during ripening of Cheddar-style cheese as influenced by a microbial rennet from rice wine. *Food Science & Nutrition, 7*(4), 1540–1550.

Water Soluble Vitamins

7

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Abstract

Vitamins support human brain, metabolism, skin, pregnancy, energy and act as antioxidants. Most of them are soluble in water: vitamins B1, B2, B3, B5, B6, B7, B9 (folate), B12 and C. While B1–B7 can be found in a variety of sources with moderate environmental impact, and vitamin C in unprocessed fruits and vegetables, others are more challenging. Deficiencies in B9 and B12 are quite common due to low consumption of wholegrains, vegetables and organ meats. Considering water and carbon footprint, new food products shifted toward plant based solutions. Since palatability is a challenge, innovative technologies produced tasty alternatives by embracing the potential of legumes and upcycled ingredients, such as pasta made with pulse flour or defatted flour (B1–B9). A curios eye has been opened on overlooked treasures such as microalgae (vitamin B12). Finally, minimally processed fruits and vegetables can be a solution to supply vitamin C and shelf-life (challenging for produce).

Keywords

B vitamins · B12 · Folate · Fruits · Meat · Vitamin C · Wholegrains

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7.1 Water Soluble Vitamins for Human Nutrition

Vitamins are essential micronutrients for human health. Micronutrients means that we only need small amounts, in the order of mg or μg, to support our daily needs. Nonetheless, they are just as important as micronutrients. Vitamins is a very broad term. Typically, we classify them in two types, based on their chemical affinity to solvents: water soluble and fat soluble (Tyśkiewicz et al., 2018). This chapter focusses on water sol-

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uble vitamins, which include vitamins B1, B2, B3, B5, B6, B7, B9, B 12 and C.

Vitamin B1 is chemically known as thiamine. Chemically, it is a sulphur-containing compound. It is mostly found in the husk and germ of wholegrains, followed by lower concentrations in foods such as meat, seafood, produce, dairy, nuts and seeds. Its deficiency leads to a disease known as beriberi, resulting in cardiovascular diseases (wet beriberi) and damage to the nervous systems (dry beriberi) (DiNicolantonio et al., 2018; NIH, 2021a). Vitamin B2 is also known as riboflavin. It is found primarily in beef liver, wholegrains and dairy. It is essential for the production of energy and the metabolism of fat soluble nutrients and iron. Its deficiency causes dysfunctions in the absorption of fats, iron and vitamins and, possibly, cancer (NIH, 2021b; Saedisomeolia & Ashoori, 2018; Thakur et al., 2017). Vitamin B3 is niacin, and it can be found in animal liver. Meat, salmon and, to lower extents, in grains. Niacin is essential for energy metabolism. When deficient in B3, humans may exhibit a skin disease known as pellagra (NIH, 2021c; Prabhu et al., 2021). Vitamin B5 is pantothenic acid; it is found abundantly in a vast variety of foods: beef liver, mushrooms, sunflower seeds, chicken, tuna, produce and many more (NIH, 2021d). Biologically, it supports the metabolism of numerous nutrients, preventing fatigue and digestive disorders (Maqbool et al., 2018). Vitamin B6 is actually a group of compounds, which are particularly important for cognitive development and brain functions. These compounds abound in chickpeas, beef liver and seafood. Deficiency in vitamin B6 can result in cardiovascular disease and even cancer (Kumrungsee et al., 2021; NIH, 2021e). Vitamin B7, biotin, is needed to metabolize glucose, amino acids and fatty acids. Its deficiency It is typically bound to protein in beef liver, eggs, seafood, pork, seeds, nuts and vegetables such as sweet potatoes, broccoli and spinach (NIH, 2021f; Scott, 2020).

Vitamin B9 is known as folic acid or folate. It is very well known for its role in pregnancy (Argyridis, 2019). It is essential for healthy development of the neural tube as well as red blood cells. Folic acid is found in beef liver, spinach, wholegrains and green leafy vegetables. Its deficiency can cause serious birth defects and megaloblastic anemia (Argyridis, 2019; NIH, 2021g).

Vitamin B12 is chemically cobalamin. It has the unique feature of a cobalt ion at the core of its structure. It is often discussed along with B9, due to their role in red blood cells development. Furthermore, it is essential for healthy brain and nervous system. Its reliable food sources are animal based: liver, meat, fish, dairy and eggs. Plant sources such as microalgae, seaweeds and fermented foods are, as of today, not consistent. Its deficiency causes serious megaloblastic anemia and brain disorders (NIH, 2021h; Rizzo & Laganà, 2020).

Vitamin C is technically an acid: ascorbic acid. It is needed as antioxidant, for healthy skin, nutrient absorption and collagen production, Deficiencies in ascorbic acid result in numerous diseases, including scurvy. Vitamin C is found only in fruits and vegetables (NIH, 2021i; Wong et al., 2020).

This chapter will present challenges and opportunities for water soluble vitamins, in terms of nutrition, sustainability and food quality. Vitamins B1, B2, B3, B5, B6 and B7 will be grouped together. Vitamins B9, B12 and C will be discussed separately due to their unique bioactivities. An example of the modern trajectory of food products rich in water soluble vitamins is depicted in Figs. 7.1–7.4.

7.2 Traditional Food Sources of Water Soluble Vitamins

7.2.1 Vitamins B1, B2, B3, B5, B6, B7

B1 (Thiamine) Brown rice is a typical example of food rich in vitamin B1. A 100 g serving if brown rice delivers half of the recommended daily intake (RDI) (NIH, 2021a) (Table 7.1). This type of rice is less refined than its white counterpart, with the outer husk removed while bran and germ are maintained (Aung, 2017). That is where vitamin B1 is found: husk, bran and germ (Balakrishna & Farid, 2020). The environmental

Fig. 7.1 Representative sources of vitamin B1: traditional (brown rice) and innovative (oat milk)

Fig. 7.2 Representative sources of vitamin B9: traditional (spinach) and innovative (lentil pasta)

footprint of brown rice is moderate, with 2,172L water required and 1.2 kg CO_2 emitted per kg of product (Kashyap & Agarwal, 2021; Mekonnen & Hoekstra, 2011). From a consumer standpoint, price is affordable at 0.35 NZD/100 g (Countdown, 2021) while sensory can be polarizing: brown colour and chewy texture may not appeal everyone (Gondal et al., 2021) along with longer cooking time than white rice, but the nutty flavour adds positively to the eating experience.

Fig. 7.3 Representative sources of vitamin B12: traditional (tuna) and innovative (microalgae such as spirulina)

Fig. 7.4 Representative sources of vitamin C: traditional (strawberries) and innovative (blackcurrant powder)

B2 (Riboflavin) Dairy products can deliver high amounts of vitamin B2, equal to 21% of the RDI (NIH, 2021b) (Table 7.1). Vitamin B2 in Greek yoghurt is highly bioavailable because calcium acts as a pathway to transport the riboflavin to the small intestine. Furthermore, milk products e.g. yoghurt contain significant concentrations of free riboflavin bound to proteins which makes it easy to absorb through the FAD and FMN cofactors of proteins (Powers, 2003). The environmental footprint is quite high, particularly in regards to carbon emissions: 4.5–6.8 kg CO_2/kg Greek yoghurt

Table 7.1 Representative food sources of water soluble vitamins: products, nutritional value (quantity, quality as % of the recommended daily intake RDI), sustainability (water and carbon footprint) and consumer acceptability (price, sensory)

	Nutrition		Sustainability		Acceptability	
Food products	quantity (per 100 g)	Quality (%RDI)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)	price (NZD/100 g)	Sensory profile
Vitamin B1 (thiamin)						
Brown rice	0.67 mg NIH (2021a)	56% NIH (2021a)	2,172 Mekonnen and Hoekstra (2011)	1.2 Kashyap and Agarwal (2021)	0.35 Countdown (2021)	Brown, chewy Gondal et al. (2021)
Vitamin B2 (riboflavin)						
Greek yoghurt	0.27 mg NIH (2021b)	21% NIH (2021b)	647 (whey) Owusu-Sekyere et al. (2017)	4.5–6.8 Houssard et al. (2020)	0.60 Countdown (2021)	Thick, creamy, slimy, smooth, sour Karagul-Yuceer and Drake (2006)
Vitamin B3 (niacin)						
Peanut butter	13 mg USDA (2019)	81% NIH (2021c)	3,740 Vanham et al. (2020)	2.5 Rahmadi et al. (2021)	1.6 Countdown (2021)	Brown, oily, nutty, spreadable Shibli et al. (2019)
Vitamin B5 (pantothenic acid)						
Beef liver	10 mg NIH (2021d)	198% NIH (2021d)	15,712 Gerbens-Leenes et al. (2013)	18–25 Buratti et al. (2017)	1.7 New Zealand Fresh (2021)	Dark red, friable, off-flavour Kolbábek et al. (2019)
Vitamin B6						
Chickpeas, canned	0.67 mg NIH (2021e)	39% NIH (2021e)	2,071 Kampman et al. (2008)	0.18 Yaghubi et al. (2021)	0.50 Countdown (2021)	Acceptable Kinfe et al. (2015)
Vitamin B7 (biotin)						
Beef liver	37µg NIH (2021f)	123% NIH (2021f)	15,712 Gerbens-Leenes et al. (2013)	18–25 Buratti et al. (2017)	1.7 New Zealand Fresh (2021)	Dark red, friable, off-flavour Kolbábek et al. (2019)
Vitamin B9 (folate)						
Spinach	437µg NIH (2021f)	109% NIH (2021f)	292 Mekonnen and Hoekstra (2011)	0.4 Wang et al. (2019)	0.6 Countdown (2021)	Green, glossy Koyama et al. (2021)
Beef liver	256µg NIH (2021f)	64% NIH (2021f)	15,712 Gerbens-Leenes et al. (2013)	18–25 Buratti et al. (2017)	1.7 New Zealand Fresh (2021)	Dark red, friable, off-flavour Kolbábek et al. (2019)
Vitamin B12 (cobalamin)						
Beef liver	84µg NIH (2021g)	3500% NIH (2021g)	15,712 Gerbens-Leenes et al. (2013)	18–25 Buratti et al. (2017)	1.7 New Zealand Fresh (2021)	Dark red, friable, off-flavour Kolbábek et al. (2019)
Tuna	11µg NIH (2021g)	458% NIH (2021g)	Not available	6.1 Rahmadi et al. (2021)	2.3 Countdown (2021)	Fishy, oily, hard, salty Caponio et al. (2010)

(continued)

Table 7.1 (continued)

	Nutrition		Sustainability		Acceptability	
Food products	quantity (per 100 g)	Quality (%RDI)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)	price (NZD/100 g)	Sensory profile
Vitamin C						
Strawberries	68 mg NIH (2021h)	76% NIH (2021h)	347 Mekonnen and Hoekstra (2011)	0.9–1.0 Mordini et al. (2009)	1.4 Countdown (2021)	Red, sweet, floral taste Jouquand et al. (2008)
Orange juice	50 mg NIH (2021h)	56% NIH (2021h)	1,018 Mekonnen and Hoekstra (2011)	0.5–0.8 Roibás et al. (2018)	0.25 Countdown (2021)	Orange, sweet, sour Kim et al. (2013)

(Houssard et al., 2020). This is due to cows farming, milk processing and whey purge: Greek yoghurt is more concentrated than other yoghurt types, thus increasing its nutritional density as well as its waste production (whey). Price is moderate (0.60 NZD/100 g) (Countdown, 2021) while the sensory experience is pleasant: creamy, smooth, thick, with sur notes (Karagul-Yuceer & Drake, 2006).

B3 (Niacin) Peanut butter can be your vitamin B3 fix. 100 g of this spread can deliver 13 mg of vitamin B3 (USDA, 2019), this means 81% of the RDI (NIH, 2021c) (Table 7.1). Obviously, nobody eats that much peanut butter, but even a regular serving size of about 40 g will cover roughly 30% of your needs. Vitamin B3 is easily absorbed into the body from the foods peanut butter. The process begins by the tissues in our body converting the absorbed B3 into the co enzyme nicotinamide adenine dinucleotide (NAD). Following this process NAD is converted to NAPD. These two coenzymes are essential within the body for oxidising the reduction of substrates in the cells. The plant based food of peanut butter provides nicotinic acid mainly and on average 2–5 mg of niacin per serving, which is highly bioavailable in the body (NIH, 2021c). Peanuts are very resourceful in terms of their water consumption due to the physical feature of them being a deep rooting crop which in turn gives them a large amount of water to draw from. In addition, they are a legume and fixate their own nitrogen, hence saving on water usage. Secondly, peanuts are a biomass crop which means they need very little foliage compared to that of other crops (seed varieties). Peanut butter therefore has a lower water footprint compared to that of other nuts. Thus means that other nut butters like almond, cashew, and hazelnut all have a higher water consumption at this stage of the supply chain whilst the primary product of the nut is being grown on farm. The water value is still high as compared to other foods (3,740 L/kg) (Vanham et al., 2020) and 2.5 kg CO_2/kg (Rahmadi et al., 2021). One of its strengths is the low price (1.65 NZD/100 g) (Countdown, 2021) and the nutty, spreadable features (Shibli et al., 2019). Peanut Butter is an acquired taste and many people either love it or dislike it. The two different categories of peanut butter include crunchy and smooth. Smooth peanut butter is very creamy and has been made into a thick fine paste whereas this is compared to crunchy peanut butter which has small segments of whole peanuts. The overall sensory profile of peanut butter is salty, sweet and with earthy undertones making you crave something to drink like a glass of water straight after due to it sticking to the roof of your mouth. Peanut butter also has a slightly savoury taste hence why it can be added to savoury meals.

B5 (Pantothenic Acid) Beef liver can provide plenty of vitamin B5. In fact, 100 g of beef liver offer double the RDI of vitamin 5 (NIH, 2021d) (Table 7.1). That is due to the ability of liver to store multiple micronutrients. This nutritional potential comes at a cost: over 15,000 L of water are needed to produce 1 kg of beef liver (Gerbens-Leenes et al., 2013), with an astounding 18–25 kg CO_2 emitted in the atmosphere (Buratti et al., 2017). Cows farming requires plenty of resources for feed, fertilizer and care of the animals. Carbon emissions result from agriculture to produce of cows' feed (crops), animals themselves (production of methane by cows digestive system) and food processing. Price is quite high (1.7 NZD/100 g) (New Zealand Fresh, 2021) while its taste is polarizing: intense, friable, with some off-flavour and bitter notes (Kolbábek et al., 2019).

B6 Chickpeas, the humble legume, are one of the grains that contain the complex of vitamin B6. As little as 100 g of cooked chickpeas provide 39% of the RDI (NIH, 2021e) (Table 7.1). Nutritionally and environmentally friendly, chickpeas production and processing require moderate amounts of water (2071 L/kg) (Kampman et al., 2008) and produce very little emissions (0.18 kg CO_2/kg) (Yaghubi et al., 2021). Furthermore, chickpeas are cheap (0.50 NZD/100 g canned chickpeas) (Countdown, 2021) and quite neutral in taste, satisfying numerus consumers.

B7 (Biotin) Beef liver once again rises to the top of micronutrient sources. A 100 g serve of beef liver cover more than the full daily need of vitamin B7 (NIH, 2021f) (Table 7.1). As stated for vitamin B5, environmental and price challenges occur, raising the need for innovative solutions to this challenge.

7.2.2 Vitamin B9 (Folate)

Spinach and beef liver are excellent sources of vitamin B9, delivering 109% and 64% of the RDI, respectively (Table 7.1). What elevates spinach to a higher rank is their extremely low footprint, both for water use (292 L/kg) (Mekonnen & Hoekstra, 2011) and carbon emission (0.4 kg CO_2/kg) (Wang et al., 2019). On top of that, spinach are affordable (0.6 NZD/100 g), with only sensory representing a challenge, due to their dark green colour and bitterness (Koyama et al., 2021).

7.2.3 Vitamin B12 (Cobalamin)

Animal food contains vitamin B12. Of course beef liver made it to the list, but also tuna is high in the ranks. The values are astonishing: 3,500% and 458% of the RDI in 100 g of food, respectively (NIH, 2021g) (Table 7.1). Luckily, there are not known cases of diseases caused by high intake of vitamin B12. The high concentration can partially solve the environmental issue, but it is not enough. Generally speaking, seafood has a lower footprint than red meat: for example, carbon emissions are three to four times lower for tuna than beef liver (Table 7.1). What these statistics don't say, is the effect of fishing and aquaculture on marine biodiversity. The growing human population is increasing the demand for fish and seafood. Consequently, more animal species are now classified as threatened to extinction, particularly in the Americas, South East Asia and Oceania. Therefore, intensive fishing and aquaculture will likely contribute to global warming (Blanchard et al., 2017).

7.2.4 Vitamin C

Fresh fruits are the most traditional way to guarantee access to vitamin C. Honourable mentions are certain vegetables such as bell peppers and broccoli, to mention a few. A 100 g serving of strawberries can guarantee 76% of the RDI, while 100 ml of orange juice provide 56% (NIH, 2021h). Most of us grew up with the knowledge that orange juice is the best source of vitamin C but, as you can see, there are even better sources, including other fruits (e.g. kiwifruit and vegetables). Keri Juicing exposes oranges to oxygen, heat and light, accelerating oxidation and degradation of vitamin C and loss of flavours. The taste retains the sweet and sour taste of oranges, but lacks the chewiness of the pulp. (Ivanova et al., 2017). Environmentally, most produce has limited impact. The only negative note is for processed fruits such as the case of orange juice, having triple water footprint than strawberries. This is due to the amount of added resources needed for processing, storage and packaging (Mekonnen & Hoekstra, 2011). In addition, juicing causes loss in insoluble nutrients such as fibre and certain phytochemicals, minerals and vitamins (Bai et al., 2013). Both fruit products are sweet and highly acceptable. Prices vary highly based on seasonality and geographical location. Local and season produce should be preferred for environmental reasons (lower footprint), enhanced sensory and nutritional properties with lower cost (less transport).

7.3 Innovative Food Sources of Water Soluble Vitamins

7.3.1 Vitamins B1, B2, B3, B5, B6, B7

B1 (Thiamine) Vitamin B1 is found in wholegrains, but their high-fibre taste might limit its consumer appeal. A pleasant exception to that is oat products. Oat milk is a growingly popular beverage, it is a good source of B1 since it is a drink made out of oats, upon blending and filtering. Therefore oat milk contains high levels of this water soluble vitamins, without the hard husk of oats. It is as high as 37% of the RDI in 100 ml (NIH, 2021a; Otis, 2021; Robinson, 1949) (Table 7.2). That means that a 250 ml serve of oat milk can fully cover our B1 daily need. Environmentally, oat harvesting only requires moderate levels of water (1,778 L) (Mekonnen & Hoekstra, 2011) while releasing very little carbon: 0.55 kg CO_2/kg (Rajaniemi et al., 2011). On top of that, oat milk is quite nice in taste. The only challenge resides in the creaminess: higher than that of other plant beverages, but still lower than that of dairy milk. Novel technologies, sometimes coupled with the use of syrups, seem to be solving this challenge, resulting in a line of so called "Barista" style oat milk.

B2 (Riboflavin) Almond Mylk is a concentrate made of almonds. Almonds contain 85% of the RDI for B2 (Karimi et al., 2021; NIH, 2021b; vvmylk, 2021) (Table 7.2). This product is meant to be used as an additive to various foods and beverages such as smoothies, coffee, pasta, ice cream etc. for its nutrition and flavour. A 250 ml serve of this concentrate will make up to 4 L of almond milk (vymylk, 2021). The benefits this product offers are an additive free almond product with a long shelf life of 1 year. Though processed into a paste/liquid form, the almond product retains a large amount of its original nutritional value. Almond Mylk is promoted as a sustainable and clean label product. The label of the product claims both 'zero waste' and 'zero added'. The 'zero waste' refers to the use of the whole almond in the product and the 'zero added' refers to no other ingredients, including preservatives, additives or artificial colours, being added to the product. This, at least, is what the company claims. In fairness, almonds do present a big challenge in terms of sustainability. Producing 1 kg of almonds involves huge loads of water (16,095 L) (Mekonnen & Hoekstra, 2011), while processing into almond milk causes large CO_2 emissions (7.1–7.2 kg/kg) (Winans et al., 2020). Therefore, almond milk concentrate can be seen as a treat, but perhaps not a staple food.

B3 (Niacin) Powdered peanut butter is just as good as peanut butter at delivering vitamin B3. The vitamin content is similar, at around 75% RDI (Bonku et al., 2020; NIH, 2021c; Nothing Naughty, 2021) and so is the environmental impact (Table 7.2). What differs is that this ingredient is upcycled, being a by-product of the peanut oil industry. Consequently, it takes pressure off the environment by transforming waste material into a new functional ingredient for human consumption. It is also high in protein and potentially open to numerous applications: bakery, confectionary, and so on.

Table 7.2 Innovative food sources of water soluble vitamins: raw materials, bioavailability (quantity, quality as % of the recommended daily intake RDI) and sustainability (water and carbon footprint)

Products	Raw materials	Bioavailability	Sustainability	
		Vitamin quantity (per 100 g) and %RDI	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)
Vitamin B1 (thiamine)				
Oat Milk	Oats	0.6 mg (37%) NIH (2021a), Otis (2021) and Robinson (1949) 10% oats	1,778 Mekonnen and Hoekstra (2011)	0.55 Rajaniemi et al. (2011)
Vitamin B2 (riboflavin)				
Almond milk concentrate	Almonds	1.1 mg (almonds) (85%) Karimi et al. (2021), NIH (2021b) and vvmylk (2021)	16,095 (almonds) Mekonnen and Hoekstra (2011)	7.1–7.2 (almond milk) Winans et al. (2020)
Vitamin B3 (niacin)				
Powdered defatted peanut butter	Peanuts	27 mg (169%) Bonku et al. (2020), NIH (2021c) and Nothing Naughty (2021)	3,740 Vanham et al. (2020)	2.5 Rahmadi et al. (2021)
Vitamin B5 (pantothenic acid)				
Lentil chips	Lentils	0.6 mg (12%) Enjoy Life Foods (2021), NIH (2021d) and USDA (2019)	5,874 Mekonnen and Hoekstra (2011)	0.29–0.60 MacWilliam et al. (2018) and Nategh et al. (2021)
Vitamin B6				
Tofu sausages	Soybeans	1.3 mg (75%) Roth-Maier et al. (2002) and Tonzu (2021)	2,145 Mekonnen and Hoekstra (2011)	0.27 Agri footprint (2021)
Vitamin B7 (biotin)				
Defatted sunflower flour	Sunflower seeds	7.5µg (25%) NIH (2021f) and Pal (2011)	3,366 Mekonnen and Hoekstra (2011)	0.88 Yousefi et al. (2017)
Vitamin B9 (folate)				
Lentil pasta	Lentils	479µg (120%) NIH (2021g) and San Remo (2021)	5,874 Mekonnen and Hoekstra (2011)	0.29–0.60 MacWilliam et al. (2018) and Nategh et al. (2021)
Roasted chickpea snacks	Chickpeas	308µg (77%) Happy Snack Company (2021) and NIH (2021g)	4,177 Mekonnen and Hoekstra (2011)	0.18 Yaghubi et al. (2021)
Vitamin B12 (cobalamin)				
Lentein powder	Duckweed (water lentils)	2.2µg (92%) Lentein (2021) and NIH (2021h)	Not available	0.40 De Beukelaar et al. (2019)
Greek yogurt	Milk	1.2µg (50%) (milk) Matte et al. (2012) and NIH (2021h)	1,020 Hayek et al. (2021)	3.0 Hayek et al. (2021)
Vitamin C				
Kiwifruit juice	Kiwifruit	62 mg (69%) Dumbravă et al. (2016) and NIH (2021i)	80–100 Soyergin (2016)	0.15–0.20 (integrated, organic) Müller et al. (2015)
Blackcurrant powder, nootropic beverage	Blackcurrants	940 mg (235%), 5 mg (6%) Ārepa (2021), NIH (2021i) and ViBeri (2021)	499 (fruit) Mekonnen and Hoekstra (2010)	Unknown

B5 (Pantothenic Acid) Lentil chips have been introduced to the crisps market in recent years along with kumara, beetroot and many more types of plant based crisps. The global vegetable crisps market is increasingly growing at a stable rate shown by the CAGR rate increasing by 9.81% between 2017 and 2021. Lentil crisps composition consists of 50% lentil flour, potato starch, sunflower oil, safflower oil, and sea salt (Countdown, 2021). They are nutritionally dense in protein, fibre, vitamins and minerals, however are fairly expensive. Lentil crisps are made by a significant amount of pressure and light to turn the lentil flour into a puffy crisp. The crisps are then baked in the oven and seasoning is added, as opposed to fried (Simply7, 2017). Lentils have become popular as people are beginning to change to plant-based diets due to the increased health benefits which this diet has to offer. There are a number of health benefits associated with the consumption of lentils. Lentils are good sources of fibre, vitamins, minerals, and contain antioxidants which reduce inflammation (Thavarajah et al., 2015). Specifically, 100 g of lentils contains 0.6 mg of B5 (12% RDI) (Enjoy Life Foods, 2021; NIH, 2021d; USDA, 2019) (Table 7.2). Lentils contain specific carbohydrates and fibre which human bodies don't have the ability to digest. They also contain antinutrients which decrease the amount of nutrients and vitamins extracted from the food meaning B5 and other nutrients is difficult to absorb form the food. The antinutrient levels can be reduced however, by dehulling, soaking, cooking, roasting, germination and/or fermentation (Patterson et al., 2017). In addition, consuming this food in combination with a source of vitamin C, such as fresh fruit or vegetables, will accelerate the degradation of the antinutrients, thus releasing micronutrients for human to absorb. The water footprint of lentils is significantly high: almost 6000 L/kg (Mekonnen & Hoekstra, 2011). Nonetheless, pulse crops are nitrate-fixing crops which enhance soil fertility and decrease the need for chemical fertilisers. Pulse crops can also reduce nitrate leaching within the soil profiles and increases the protein within the wheat which in turn increases revenue generated from the crop (Ding et al., 2018). This results in a negligible carbon emission ranging from 0.29 to 0.60 kg CO_2/kg (MacWilliam et al., 2018;融Nategh et al., 2021).

Vitamin B7 (Biotin) While beef liver is an excellent source of vitamin B7, plants do contribute to its intake as well. In this regard, lower amounts of micronutrients and lower footprint are the result. A good example? Defatted sunflower flour. This is a great case of upcycling. The oil industry leaves behind plenty of nutrients in a fibrous, hard to cook with meal. Appropriate processing, such as extrusion and high pressure, can micronize (reduce in size) the insoluble fibre, making it more soluble. The result is a highly versatile flour, which also delivers vitamin B7: sunflower seeds contain 25% of the RDI (NIH, 2021f; Pal, 2011). Once the oil is removed, it is possible that this number will increase, possibly double (half of these seeds is oil), nut it hasn't been verified yet. This comes with potential applications such as high protein pasta, featuring a characteristic dark grey colour. To testify this, a USA company (Planetarians) provided the ingredient to two Italian pasta companies (Amadori and Barilla) (Food Navigator, 2019). Sunflower seeds have moderate impact on the environment: about 3000 L water and less than 1 kg CO_2 produced per kg (Mekonnen & Hoekstra, 2011; Yousefi et al., 2017). Therefore, the use of their upcycled flour could result in low impact source of vitamin B7.

7.3.2 Vitamin B9 (Folate)

As states above, pulses like lentils are a powerhouse for B vitamins. This include B9, with as much as 120% of the RDI in 100 g of lentils (NIH, 2021g) (Table 7.2). It is not just chips, but also pasta (San Remo, 2021). Lentil pasta is part of a recent trend toward alternative protein, high fibre and gluten-free. The nutritional benefits are many, while the taste is not the same as traditional pasta, being chewy and earthy. Therefore, this product should be consumed as something new rather than a new pasta type. There is a catch though! Pasta is cooked by boiling. Since B9 is water soluble chances are that it might leach into the cooking water, thus never being consumed. There are currently no studies on this, but it is a legitimate concern. While lentil pasta might be a great source of protein and fibre, it may not be the best way to cook your lentils when looking at water soluble vitamins.

Therefore, a better approach could be roasting your pulses. This is the case of roasted chickpea snacks (Happy Snack Company, 2021). Chickpeas contain 77% of the B9 RDI (NIH, 2021g) (Table 7.2). The roasting process is not known to decrease B9 content, thus making roasted chickpeas a good choice in this sense. Environmentally, chickpeas require less water than other pulses and are also responsible for lower carbon emissions (0.18 vs. 0.29–0.60 kg CO_2/kg) (MacWilliam et al., 2018; Nategh et al., 2021; Yaghubi et al., 2021), although this parameter should factor in industrial process. Chickpeas perform well in locations with dry conditions, and prefer a well-draining soil type, therefore demanding less water. This is due to the plants having a deep root system (Ahmad et al., 2005).

7.3.3 Vitamin B12 (Cobalamin)

It is well-established that only animal foods are reliable sources of vitamin B12. Microbes produce it, animals store it in their flesh, eggs and milk. Interestingly though, there have been cases where plant contained this nutrient, such as for duckweed. Duckweed/water lentils have been dried and turned into powder form to incorporate into smoothies as a form of a vegan B12 but also in multiple other vitamins and minerals, estimating a B12 content equal to 92% RDI (Lentein, 2021; NIH, 2021g) (Table 7.2). The acceptability of this B12 source is still yet to be completely assessed but beginning studies have been conducted stating that consumers had a generally positive mindset towards duckweed as human food when seen in a fitting meal and upon informing consumers on the positive nutritional and environmental impacts the product has there was a decreased acceptability in non-fitting meals. Its individual or mixed components of methylcobalamin and hydroxocobalamin provided by most likely a symbiotic relationship thought to be due to photosynthetic eukaryotes (Kaplan et al., 2019). These two forms of vitamin B12 in the raw material can also be considered to have relatively the same degree of bioavailability as that of pure methylcobalamin powder (56–89%) (Obeid et al., 2015). Studies show that the bioavailability of intracellular methylating metabolites is determined based on individual metabolisms and single nucleotide polymorphisms rather than being dependent on the form itself. (Paul & Brady, 2017). Duckweed/Water lentils have a minimal carbon footprint, estimated at 0.4 kg CO_2/kg (De Beukelaar et al., 2019). Its high growth rate and its tolerance of extreme conditions as well as the ability for the materials cultivation in basins on non-arable land make it a highly sustainable product due to its lack of farmland needed and minimal control of general conditions. (De Beukelaar et al., 2019).

Milk is also a great source of B12, and it can be used to make things such as Greek yogurt. Milk itself contains methylcobalamin. Vitamin B12, in milk, is bound to very specific protein carriers such as transcobalamin and haptocorrin (Fedosov et al., 2019). These types of proteins improve the availability of B12 in milk. This is due to the pH stability and slow proteolysis which help the nutritional availability of B12 in the milk. (Fedosov et al., 2019). Milk itself delivers half of the RDI, in as little as 100 g (Matte et al., 2012; NIH, 2021h) (Table 7.2). Environmentally, it takes 1,020 litres of water to produce a litre of Greek yoghurt (Hayek et al., 2021). This is extremely unstainable, and leads to a great amount of water waste each year. There is also concern about the emissions that cows are putting into the environment, with a total of 3.0 kg CO_2/kg (Hayek et al., 2021). This is contributing heavily to the agriculture greenhouse gas emissions, which is contributing dramatically to climate change. The biological oxygen demand reaches around 6.9 and $48gL^{-1}$, and the chemical oxygen demand reaches 12 and 95 g/L for dairy production (Fedosov et al., 2019). This is extremely detrimental to the health of the environment.

7.3.4 Vitamin C

Kiwifruit offers plenty of vitamin C: 69% of the RDI in a 100 g fruit (Dumbravă et al., 2016; NIH, 2021i) (Table 7.2). The absorption rate of vitamin C in the human body is related to the intake (Vissers et al., 2013). The absorption rate can reach 100% when the intake is 30–60 mg. When the intake is 90 mg, the absorption rate is reduced to about 80%. When the intake is 1,500 mg, the matching absorption rate is 49%. The body can only absorb 36% of nutrients when the intake is 3,000 mg, and when the absorption rate is 16%, the intake is 12,000 mg. The daily intake of vitamin C by adults is 100 mg, a kiwi fruit weighs about 160 g, and 100 g of kiwi fruit contains 62 mg of vitamins. Therefore, eating a kiwi fruit every day can supplement vitamin C for a day. But because vitamin C is easily destroyed regardless of whether it exists outside or inside the body. Although a large amount of ingestion is not harmful to the human body, it should not be taken too much at once, because after a large amount of ingestion, it will not all be absorbed, and the final result is still excreted from the body. The best way is to separate the time and use it in segments, so as to increase the absorption rate of vitamin C in the body (Vissers et al., 2013). Environmentally, it is a feather-like light touch: 80–100 L water are needed and 0.15–0.50 kg CO_2 are emitted per kg of kiwifruit harvested (Müller et al., 2015; Soyergin, 2016). It likes a cool and humid climate, with annual precipitation exceeding 800 mm and relative humidity exceeding 70%.

Blackcurrant products (beverages, freeze-dried powders) are relatively new to the market and slowly increasing in popularity (Ārepa, 2021; ViBeri, 2021). A study on the ascorbic acid content of freeze dried and air dried berries found that its levels were consistently higher in organically and sustainably grown crops compared to conventionally grown. It also found that both freeze-dried and air dried berries demonstrated a statistically significant decrease in vitamin C levels compared to frozen, but freeze dried was still better than air dried (Asami et al., 2003). The problem here is cost and sustainability. ViBeri's "New Zealand Organic Blackcurrant Berries" cost NZD 14.13/100 g. Moreover, freeze-drying involves large energy expenditures, carbon emissions and water waste, unless it is recycled. Ārepa also produces a freeze dried blackcurrant product, the "Freeze Dried Neuroberry". The Neuroberry product too costs a lot: NZD 23.3/100 g. The price issue can be overcome by the low serving size needed of about 10 g. Drying still represents a large environmental burden so alternative concentration techniques should be considered. The benefit is enhanced shelf-life and no need for cold storage (freezer or fridge). Blackcurrants have minimal impact, with only 500 L water required per kg harvested (Mekonnen & Hoekstra, 2010), while data on the carbon emissions was not found. This leaves some room for processing. Shelf-stable blackcurrant products could be a new sustainable way to Vitamin C, if more efficient technologies for water removal will be found.

7.4 Conclusions

Water soluble vitamins are a large group. Vitamins B1, B2, B3, B5, B6 and B7 are mostly found in wholegrains, but also diary and meat. Vitamins B9 and B12 often affect similar health mechanisms. While B9 (folate) is abundant in wholegrains, seafood and animal liver, B12 is prerogative of animal food (liver, dairy, eggs). Similarly, fruit and vegetables are prerogative for vitamin C. Innovative food products propose plant-based solutions for B vitamins based on nuts, pulses and defatted seeds. The last two are more sustainable than nuts, environmentally, requiring less water, while delivering similar, if not superior, nutritional benefits. Nonetheless, they are more challenging in terms of taste and texture. It is fascinating that B12 was found in a plant based sources (microalgae such as spirulina and duckweed) although research is new so further data must be collected to guarantee adequate supply. The extremely low carbon footprint of microalgae, due to their ability to sequester carbon, makes them interesting, when compared to Greek yoghurt, yet sensory challenges persist. Finally, vitamin C innovations are not as exciting, perhaps relying on a wide array of sustainable options, based on local produce.

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References

Agri footprint. (2021). *Environmental footprint of certified sustainably produced Brazilian soy*. https://www.agri-footprint.com/2020/08/12/environmental-footprint-of-certified-sustainably-produced-brazilian-soy/. Accessed on 9 Nov 2021.

Ahmad, F., Gaur, P. M., & Croser, J. (2005). Chickpea (*Cicer arietinum l.*). In *Genetic resources, chromosome engineering, and crop improvement-grain legumes* (Vol. 1, pp. 187–217). CRC Press.

Ārepa. (2021). *Ārepa Lite + Sparkling*. https://drinkarepa.com/products/arepa-nootropic-drinks-sparkling?variant=39306359898299. Accessed on 10 Nov 2021.

Argyridis, S. (2019). Folic acid in pregnancy. *Obstetrics, Gynaecology & Reproductive Medicine, 29*(4), 118–120.

Asami, D. K., Hong, Y. J., Barrett, D. M., & Mitchell, A. E. (2003). Comparison of the total phenolic and ascorbic acid content of freeze-dried and air-dried marionberry, strawberry, and corn grown using conventional, organic, and sustainable agricultural practices. Journal of Agricultural and Food Chemistry, 51(5), 1237–1241.

Aung, Y. (2017). Food losses in rice milling. In *Crop improvement* (pp. 287–303). Springer.

Bai, J., Manthey, J. A., Ford, B. L., Luzio, G., Cameron, R. G., Narciso, J., & Baldwin, E. A. (2013). Effect of extraction, pasteurization and cold storage on flavonoids and other secondary metabolites in fresh orange juice. *Journal of the Science of Food and Agriculture, 93*(11), 2771–2781.

Balakrishna, A. K., & Farid, M. (2020). Enrichment of rice with natural thiamine using high-pressure processing (HPP). *Journal of Food Engineering, 283*, 110040.

Blanchard, J. L., Watson, R. A., Fulton, E. A., Cottrell, R. S., Nash, K. L., Bryndum-Buchholz, A., et al. (2017). Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture. *Nature Ecology & Evolution, 1*(9), 1240–1249.

Bonku, R., Mikiashvili, N., & Yu, J. (2020). Impacts of protease treatment on the contents of tocopherols and B vitamins in peanuts. *Journal of Food Research, 9*(6), 1–12.

Buratti, C., Fantozzi, F., Barbanera, M., Lascaro, E., Chiorri, M., & Cecchini, L. (2017). Carbon footprint of conventional and organic beef production systems: An Italian case study. *Science of the Total Environment, 576*, 129–137.

Caponio, F., Bilancia, M. T., Summo, C., Gomes, T., & Pasqualone, A. (2010). A survey of in-oil canned tuna quality by sensory analysis and the determination of the oxidative degradation of the liquid medium. *International Journal of Food Properties, 13*(4), 672–681.

Countdown. (2021). https://shop.countdown.co.nz/. Accessed on 8 Nov 2021.

De Beukelaar, M. F., Zeinstra, G. G., Mes, J. J., & Fischer, A. R. (2019). Duckweed as human food. The influence of meal context and information on duckweed acceptability of Dutch consumers. Food Quality and Preference, 71, 76–86.

Ding, D., Zhao, Y., Guo, H., Li, X., Schoenau, J., & Si, B. (2018). Water footprint for pulse, cereal, and oilseed crops in Saskatchewan, Canada. *Water, 10*(11), 1609.

DiNicolantonio, J. J., Liu, J., & O'Keefe, J. H. (2018). Thiamine and cardiovascular disease: A literature review. *Progress in Cardiovascular Diseases, 61*(1), 27–32.

Dumbravă, D. G., Moldovan, C., Raba, D. N., Popa, V. M., & Drugă, M. (2016). Evaluation of antioxidant activity, polyphenols and vitamin C content of some exotic fruits. *Journal of Agroalimentary Processes and Technologies, 22*(1), 13–16.

Enjoy Life. (2021). *Lentil chips*. https://enjoylifefoods.com/collections/lentil-chips. Accessed on 9 Nov 2021.

Fedosov, S. N., Nexo, E., & Heegaard, C. W. (2019). Vitamin B12 and its binding proteins in milk from cow and buffalo in relation to bioavailability of B12. *Journal of Dairy Science, 102*(6), 4891–4905.

Food Navigator. (2019). *Planetarians ties-up with Barilla, Amadori to innovate with up-cycled sunflower flour*. https://www.foodnavigator.com/Article/2019/03/19/Planetarians-ties-up-with-Barilla-Amadori-to-innovate-with-up-cycled-sunflower-flour. Accessed on 2 Dec 2021.

Gerbens-Leenes, P. W., Mekonnen, M. M., & Hoekstra, A. Y. (2013). The water footprint of poultry, pork and beef: A comparative study in different countries and production systems. *Water Resources and Industry, 1*, 25–36.

Gondal, T. A., Keast, R. S., Shellie, R. A., Jadhav, S. R., Gamlath, S., Mohebbi, M., & Liem, D. G. (2021). Consumer acceptance of Brown and White Rice varieties. *Food, 10*, 1–19.

Happy Snack Company. (2021). *Roasted chickpeas*. https://happysnackcompany.com.au/product/crunchy-roasted-chic-peas-lightly-salted-6-by-25g-packs/. Accessed on 10 Nov 2021.

Hayek, J., El Bachawati, M., & Manneh, R. (2021). Life cycle assessment and water footprint scarcity of yogurt. *Environment, Development and Sustainability, 23*, 1–32.

Houssard, C., Maxime, D., Benoit, S., Pouliot, Y., & Margni, M. (2020). Comparative life cycle assessment of five Greek yogurt production systems: A perspective beyond the plant boundaries. *Sustainability, 12*(21), 9141.

Ivanova, N. N., Khomich, L. M., & Perova, I. B. (2017). Orange juice nutritional profile. *Voprosy Pitaniia, 86*(6), 103–113.

Jouquand, C., Chandler, C., Plotto, A., & Goodner, K. (2008). A sensory and chemical analysis of fresh strawberries over harvest dates and seasons reveals factors that affect eating quality. *Journal of the American Society for Horticultural Science, 133*(6), 859–867.

Kampman, D. A., Hoekstra, A. Y., & Krol, M. S. (2008). *The water footprint of India* (Value of water research report series, 32) (pp. 1–152). Unesco-IHE Institute for Water Education.

Kaplan, A., Zelicha, H., Tsaban, G., Meir, A. Y., Rinott, E., Kovsan, J., et al. (2019). Protein bioavailability of Wolffia globosa duckweed, a novel aquatic plant – A randomized controlled trial. *Clinical Nutrition, 38*(6), 2576–2582.

Karagul-Yuceer, Y., & Drake, M. (2006). Sensory analysis of yogurt. In *Manufacturing yogurt and fermented milks* (pp. 265–270). Wiley-Blackwell.

Karimi, Z., Firouzi, M., Dadmehr, M., Javad-Mousavi, S. A., Bagheriani, N., & Sadeghpour, O. (2021). Almond as a nutraceutical and therapeutic agent in Persian medicine and modern phytotherapy: A narrative review. *Phytotherapy Research, 35*(6), 2997–3012.

Kashyap, D., & Agarwal, T. (2021). Carbon footprint and water footprint of rice and wheat production in Punjab, India. *Agricultural Systems, 186*, 102959.

Kim, M. K., Lee, Y. J., Kwak, H. S., & Kang, M. W. (2013). Identification of sensory attributes that drive consumer liking of commercial orange juice products in Korea. *Journal of Food Science, 78*(9), S1451–S1458.

Kinfe, E., Singh, P., & Fekadu, T. (2015). Physicochemical and functional characteristics of desi and kabuli chickpea (*Cicer arietinum L.*) cultivars grown in Bodity, Ethiopia and sensory evaluation of boiled and roasted products prepared using chickpea varieties. *International Journal of Current Research in Biosciences and Plant Biology, 2*(4), 21–29.

Kolbábek, P., Maxová, P., Kouřimská, L., Lukešová, D., & Kotrba, R. (2019). Sensory evaluation of liver/meat Pâté made from fresh or frozen eland meat and beef. *Scientia Agriculturae Bohemica, 50*(2), 71–79.

Koyama, K., Tanaka, M., Cho, B. H., Yoshikawa, Y., & Koseki, S. (2021). Predicting sensory evaluation of spinach freshness using machine learning model and digital images. *PLoS One, 16*(3), e0248769.

Kumrungsee, T., Zhang, P., Yanaka, N., Suda, T., & Kato, N. (2021). Emerging cardioprotective mechanisms of vitamin B6: A narrative review. *European Journal of Nutrition, 61*(2), 1–9.

Lentein. (2021). *Water lentils*. https://www.parabel.com/lentein/. Accessed on 10 Nov 2021.

MacWilliam, S., Parker, D., Marinangeli, C. P., & Trémorin, D. (2018). A meta-analysis approach to examining the greenhouse gas implications of including dry peas (*Pisum sativum* L.) and lentils (*Lens culinaris* M.) in crop rotations in western Canada. *Agricultural Systems, 166*, 101–110.

Maqbool, M. A., Aslam, M., Akbar, W., & Iqbal, Z. (2018). Biological importance of vitamins for human health: A review. *Journal of Agriculture and Basic Sciences, 2*(3), 50–58.

Matte, J. J., Guay, F., & Girard, C. L. (2012). Bioavailability of vitamin B12 in cows' milk. *British Journal of Nutrition, 107*(1), 61–66.

Mekonnen, M. M., & Hoekstra, A. Y. (2010). *The green, blue and grey water footprint of crops and derived crop products* (Value of water research report series no. 47). UNESCO-IHE Institute for Water Education. https://www.waterfootprint.org/media/downloads/Report47-WaterFootprintCrops-Vol1.pdf. Accessed on 29 May 2021

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences, 15*(5), 1577–1600.

Mordini, M., Nemecek, T., Gaillard, G., Bouman, I., Campina, R. F., Brovelli, E., et al. (2009). *Carbon & water footprint of oranges and strawberries*. Federal Department of Economic Affairs.

Müller, K., Holmes, A., Deurer, M., & Clothier, B. E. (2015). Eco-efficiency as a sustainability measure for kiwifruit production in New Zealand. *Journal of Cleaner Production, 106*, 333–342.

Nategh, N. A., Banaeian, N., Gholamshahi, A., & Nosrati, M. (2021). Sustainability assessment and optimization of legumes production systems: Energy, greenhouse gas emission and ecological footprint analysis. *Renewable Agriculture and Food Systems, 36*, 1–11.

New Zealand Fresh. (2021). https://newzealandfresh.sg/products/frozen-beef-liver-1kg-pack. Accessed on 23 Sept 2021.

NIH. (2021a). *Thiamin*. https://ods.od.nih.gov/factsheets/Thiamin-HealthProfessional/. Accessed on 8 Nov 2021.

NIH. (2021b). *Riboflavin*. https://ods.od.nih.gov/factsheets/Riboflavin-HealthProfessional/. Accessed on 8 Nov 2021.

NIH. (2021c). *Niacin*. https://ods.od.nih.gov/factsheets/Niacin-HealthProfessional/. Accessed on 8 Nov 2021.

NIH. (2021d). *Pantothenic acid*. https://ods.od.nih.gov/factsheets/PantothenicAcid-HealthProfessional/. Accessed on 8 Nov 2021.

NIH. (2021e). *Vitamin B6*. https://ods.od.nih.gov/factsheets/Biotin-HealthProfessional/. Accessed on 8 Nov 2021.
NIH. (2021f). *Biotin*. https://ods.od.nih.gov/factsheets/VitaminB6-HealthProfessional/. Accessed on 8 Nov 2021.
NIH. (2021g). *Folate*. https://ods.od.nih.gov/factsheets/Folate-HealthProfessional/. Accessed on 8 Nov 2021.
NIH. (2021h). *Vitamin B12*. https://ods.od.nih.gov/factsheets/VitaminB12-HealthProfessional/. Accessed on 9 Nov 2021.
NIH. (2021i). *Vitamin C*. https://ods.od.nih.gov/factsheets/VitaminC-HealthProfessional/. Accessed on 9 Nov 2021.
Obeid, R., Fedosov, S. N., & Nexo, E. (2015). Cobalamin coenzyme forms are not likely to be superior to cyano- and hydroxyl-cobalamin in prevention or treatment of cobalamin deficiency. *Molecular Nutrition & Food Research, 59*(7), 1364–1372.
Otis. (2021). https://otisoatmilk.co.nz/. Accessed on 9 Nov 2021.
Owusu-Sekyere, E., Jordaan, H., Chouchane, H. (2017). Evaluation of water footprint and economic water productivities of dairy products of South Africa. *Ecological Indicators* 8332-8340 S1470160X17304545 10.1016/j.ecolind.2017.07.041
Pal, D. (2011). Sunflower (Helianthus annuus L.) seeds in health and nutrition. In *Nuts and seeds in health and disease prevention* (pp. 1097–1105). Academic.
Patterson, C. A., Curran, J., & Der, T. (2017). Effect of processing on antinutrient compounds in pulses. *Cereal Chemistry, 94*(1), 2–10.
Paul, C., & Brady, D. M. (2017). Comparative bioavailability and utilization of particular forms of B12 supplements with potential to mitigate B12-related genetic polymorphisms. *Integrative Medicine: A Clinician's Journal, 16*(1), 42.
Powers, H. J. (2003). Riboflavin (vitamin B-2) and health. *The American Journal of Clinical Nutrition, 77*(6), 1352–1360.
Prabhu, D., Dawe, R. S., & Mponda, K. (2021). Pellagra a review exploring causes and mechanisms, including isoniazid-induced pellagra. *Photodermatology, Photoimmunology & Photomedicine, 37*(2), 99–104.
Rahmadi, P., Widodo, A. A., & Marzuki, R. (2021). Carbon footprint of tuna and tuna like production landed based at Bitung fish port. In *IOP conference series: Earth and environmental science* (Vol. 800, No. 1, p. 012004). IOP Publishing.
Rajaniemi, M., Mikkola, H., & Ahokas, J. (2011). Greenhouse gas emissions from oats, barley, wheat and rye production. *Agronomy Research, 9*, 189–195.
Rizzo, G., & Laganà, A. S. (2020). A review of vitamin B12. In *Molecular nutrition* (pp. 105–129). Academic.
Robinson Jr, E. J. (1949). Notes on the life history of a brachylaemid trematode. Science, 109(2820), p. 32.
Roibás, L., Rodríguez-García, S., Valdramidis, V. P., & Hospido, A. (2018). The relevance of supply chain characteristics in GHG emissions: The carbon footprint of Maltese juices. *Food Research International, 107*, 747–754.
Roth-Maier, D. A., Kettler, S. I., & Kirchgessner, M. (2002). Availability of vitamin B 6 from different food sources. *International Journal of Food Sciences and Nutrition, 53*(2), 171–179.
Saedisomeolia, A., & Ashoori, M. (2018). Riboflavin in human health: A review of current evidences. *Advances in Food and Nutrition Research, 83*, 57–81.
San Remo. (2021). *Pulse pasta red lentil spirals*. https://sanremo.co.nz/products/pulse-pasta-red-lentils-spirals/. Accessed on 10 Nov 2021.
Scott, W. C. (2020). Literature review of both classic and novel roles of biotin (vitamin B7) in cellular processes. *UTSC's Journal of Natural Sciences, 1*(1), 45–51.
Shibli, S., Siddique, F., Raza, S., Ahsan, Z., & Raza, I. (2019). Chemical composition and sensory analysis of peanut butter from indigenous peanut cultivars of Pakistan. *Pakistan Journal of Agricultural Research, 32*(1), 159.
Simply7. (2017). *FAQ*. https://international.simply7snacks.com/faq/. Accessed on 2 Dec 2021.
Soyergin, S. (2016). Effect of organic practices on kiwi productivity levels and some oil properties for organic kiwi cultivation. *Agriculture and Food, 4*, 394–401.
Thakur, K., Tomar, S. K., Singh, A. K., Mandal, S., & Arora, S. (2017). Riboflavin and health: A review of recent human research. *Critical Reviews in Food Science and Nutrition, 57*(17), 3650–3660.
Thavarajah, D., Johnson, C. R., McGee, R., & Thavarajah, P. (2015). Phenotyping nutritional and antinutritional traits. In *Phenomics in crop plants: Trends, options and limitations* (pp. 223–233). Springer.
Tonzu. (2021). *Vegan Sausages*. https://tonzu.co.nz/product-category/vegan-sausages/. Accessed on 9 Nov 2021.
Tyśkiewicz, K., Dębczak, A., Gieysztor, R., Szymczak, T., & Rój, E. (2018). Determination of fat-and water-soluble vitamins by supercritical fluid chromatography: A review. *Journal of Separation Science, 41*(1), 336–350.
USDA. (2019). *Peanut butter*. https://fdc.nal.usda.gov/fdc-app.html#/food-details/172470/nutrients. Accessed on 8 Nov 2021.
Vanham, D., Mekonnen, M. M., & Hoekstra, A. Y. (2020). Treenuts and groundnuts in the EAT-lancet reference diet: Concerns regarding sustainable water use. *Global Food Security, 24*, 100357.
ViBeri. (2021). *Organic blackcurrant powder*. https://viberi.co.nz/collections/viberi-products/products/organic-blackcurrant-powder-450g-loose-powder. Accessed on 3 Dec 2021.
Vissers, M. C., Carr, A. C., Pullar, J. M., & Bozonet, S. M. (2013). The bioavailability of vitamin C from kiwifruit. *Advances in Food and Nutrition Research, 68*, 125–147.
vvmylk. (2021). https://vvmylk.nz/product/almond-mylk-concentrate-250ml-makes-4l/. Accessed on 9 Nov 2021.

Wang, Z. B., Zhang, J. Z., & Zhang, L. F. (2019). Reducing the carbon footprint per unit of economic benefit is a new method to accomplish low-carbon agriculture. A case study: Adjustment of the planting structure in Zhangbei County, China. *Journal of the Science of Food and Agriculture, 99*(11), 4889–4897.

Winans, K. S., Macadam-Somer, I., Kendall, A., Geyer, R., & Marvinney, E. (2020). Life cycle assessment of California unsweetened almond milk. *The International Journal of Life Cycle Assessment, 25*(3), 577–587.

Wong, S. K., Chin, K. Y., & Ima-Nirwana, S. (2020). Vitamin C: A review on its role in the management of metabolic syndrome. *International Journal of Medical Sciences, 17*(11), 1625.

Yaghubi, E., Carboni, S., Snipe, R. M., Shaw, C. S., Fyfe, J. J., Smith, C. M., et al. (2021). Farmed mussels: A nutritive protein source, rich in omega-3 fatty acids, with a low environmental footprint. *Nutrients, 13*(4), 1124.

Yousefi, M., Khoramivafa, M., & Damghani, A. M. (2017). Water footprint and carbon footprint of the energy consumption in sunflower agroecosystems. *Environmental Science and Pollution Research, 24*(24), 19827–19834.

8 Fat Soluble Vitamins

Luca Serventi, Yuxuan Wang, Ziqian Feng, and Mary Tanyitiku

Abstract

Vitamin A comes from carrots, D from dairy, E from nuts and K from spinach? True, but there is way more to it. Liver is rich in numerous vitamins, but raising a cow has a different environmental load to growing produce, as much as they differ in taste and price. Vitamin D is technically a hormone, and it's the result of sun exposure: humans, animals, plants, they all can synthesize it. Nuts offer plenty of vitamin E and they are tasty, but how much water does it take to grow them? Perhaps oilseeds can be considered as sustainable alternatives, not a replacement, just another option. Dietary sourcing of vitamin K is typically sustainable, but it can get more creative to increase consumer appeal. Green leafy vegetables can be used to make tasty dips or even flours that improve low gluten baked goods. Options are available, specific knowledge is discussed in this chapter.

Keywords

Dairy · Meat · Plant based · Vitamin A · Vitamin D · Vitamin E · Vitamin K

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8.1 Fat Soluble Vitamins for Human Nutrition

Vitamins are essential nutrients for human health. Among these, certain compounds are fat soluble (National Research Council, 1989). That means that fat, or lipid, is needed to allow their absorption. The list includes the following four groups:

- Vitamin A (retinol, retinyl esters and its precursors from carotenoids);
- Vitamin D (cholecalciferol or D3 and its precursor ergocalciferol or D2);
- Vitamin E (α-, β-, δ- and γ-tocopherol, α-, β-, δ- and γ-tocotrienol);
- Vitamin K (phylloquinone or K1 and menaquinone or K2).

Overall, they interact with the gut microbiota in a positive manner. Fat soluble vitamins influence the activity of gut microorganisms, modulating the immune response and stimulating anti-inflammatory activities as well as the synthesis of antimicrobial peptides (Stacchiotti et al., 2021). They also exert several functionalities, discussed specifically in the following paragraphs.

Vitamin A is needed for eyes health, and it also contributes to the metabolism of carbohydrates, lipids and protein and it inhibits tumor growth. It is mostly found in fruits and vegetables in the precursor form provitamin A or β-carotene. It is also found in animal foods in the form of retinyl esters (Albahrani & Greaves, 2016; Wiseman et al., 2017).

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Vitamin D is a fascinating vitamin, since it is a hormone and it is synthesized by the sun. The D2 form is the result of ultraviolet (UV) irradiation of plant sterols that are subsequently eaten (directly by humans or indirectly through animals then consumed as food). The D3 form is synthesized similarly, via exposure to the sun, but with a different substrate: dehydrocholesterol found in human skin (Albahrani & Greaves, 2016; Müller et al., 2011; National Research Council, 1989). Vitamin D supports healthy bones by enhancing calcium and phosphorous absorption (Lucas et al., 2014; Müller et al., 2011). In addition, vitamin D strengthens the immune response and resistance to infections (Lucas et al., 2014).

Vitamin E is mostly known as antioxidant, eliminating free radicals. It is also essential in fighting inflammation and supporting vascular health. It favours the development of healthy red blood cells and prevent cardiovascular disease. Specifically, it inhibits atherosclerosis, which is the accumulation of fats, particularly saturated and cholesterol, in the arteries (Albahrani & Greaves, 2016; Dutta and Dutta, 2003).

Vitamin K is known for its role in allowing blood coagulation in case of cuts and injuries (National Research Council, 1989). It is essential for the synthesis of proteins responsible for the following bioactivities: procoagulant, anticoagulant, artery calcification inhibition, bone health and cell growth (Vermeer, 2012).

This chapter addresses the food sources of fat soluble vitamins, with a holistic approach that compares them for nutritional quality, environmental impact and consumer acceptance. An example of the modern trajectory of food products containing fat soluble vitamins is depicted in Figs. 8.1, 8.2, 8.3, and 8.4.

8.2 Traditional Food Sources of Fat Soluble Vitamins

8.2.1 Vitamin A

Two representative sources were chosen: one from the animal kingdom (beef liver) and one from the plant kingdom (carrots). Quantity wise, beef liver is one of the highest sources of vitamin

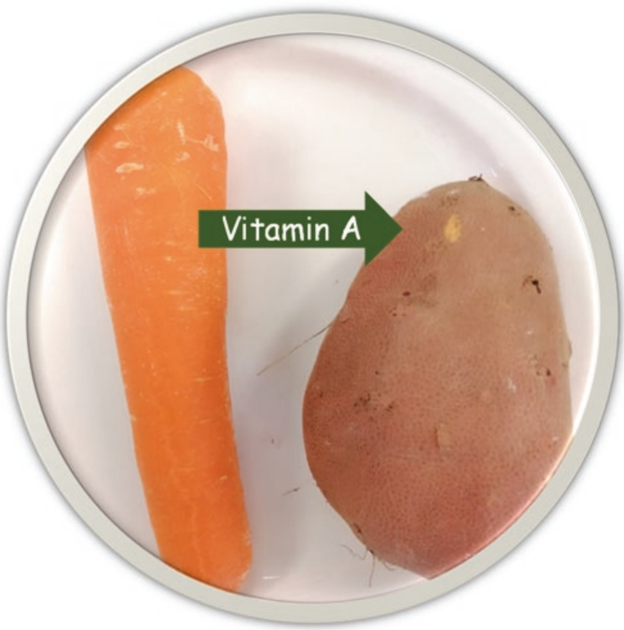

Fig. 8.1 Representative sources of Vitamin A: traditional (carrots) and innovative (sweet potatoes as source of flour)

Fig. 8.2 Representative sources of Vitamin D: traditional (milk) and innovative (brown mushrooms)

Fig. 8.3 Representative sources of Vitamin E: traditional (almonds) and innovative (almond butter)

A, delivering as much as 7.7 mg/100 g: that is 860% of the recommended daily intake (RDI) (NIH, 2021a). This number is 20 times higher than that of carrots (Table 8.1). Animal foods such as liver, chicken, dairy and eggs contain preformed vitamin A, which is easily absorbed. Plant sources such as green leafy vegetables, carrots and sweet potatoes contain the precursor called provitamin A, which needs conversion (Olson et al., 2021). Therefore, beef liver delivers more of this nutrient and in a form that is more easily absorbable. It is important to state that vitamin A, if consumed in excessive amounts, such as 900 mg, can be toxic (Olson et al., 2021).

Environmental impact is the big challenge here. Producing 1 kg of beef liver can demand as much as 15,712 L of water and results in emissions of 18–25 kg CO_2 (Buratti et al., 2017; Gerbens-Leenes et al., 2013. On the contrary, carrots require less than 200 L of water and only cause emissions of 0.11–0.31 kg CO_2, while delivering 40% of the RDI with a 100 g portion

Fig. 8.4 Representative sources of Vitamin K: traditional (kale, spinach) and innovative (green vegetables dip)

size (NIH, 2021a). Considering the relevant amounts found in carrots, vegetables seem to be a reasonable source of vitamin A in terms of nutrition and sustainability. Their price is sustainable too, being 7 times lower for carrots than beef liver: 0.25 vs. 1.7 NZD/100 g (Countdown, 2021; New Zealand Fresh, 2021).

Taste is a key element. Liver has strong bitter, acidulous taste that may drive some consumers away, just like for carrots earthy notes (Condurso et al., 2020; Wiklund et al., 2003). Nonetheless, other animal sources are far juicier and tastier (dairy, chicken and so on) directing people toward these choices. Vegetables have potential if cooked properly, accordingly to their pros and cons. For example, carrots earthiness makes them less appealing, but their sweetness and bright colour are attractive (Condurso et al., 2020).

8.2.2 Vitamin D

Animal foods such as dairy and fatty fish are notoriously indicated as ways to obtain Vitamin D via diet. Quantity-wise, fatty fish are the big winner. For example, a 100 g serve of trout can deliver 95% of the 20 μg daily dose (NIH, 2021b). Contrary to popular belief, dairy is not a major source of vitamin D. On average, cow's milk contains 1.2 μg of vitamin D (NIH, 2021b). If considering a 250 ml serving size, that adds up to 3 μg, which is 15% of the RDI.

The environmental factors lean even more against dairy: water footprint varies, based on farming techniques, from 2,872 L/kg (industrial farming) to 7,645 L/kg (grazing), while trout only requires 20 L/kg (Ibidhi & Salem, 2020; Pérez-Rincón et al., 2017). That is a massive amount of water required. This is due to the animal size, being much larger for cows, and their need for food, explaining why grazing is more demanding of water than industrial farming. On the other hands, carbon emissions are far worse for fish, with the case of trout farming yielding 4–15 kg CO_2/kg vs. 1.0–1.5 kg CO_2/L milk (Flysjö et al., 2011; Liu et al., 2016; Poore and Nemecek (2018). Feed production causes more than half of the emissions, with transport and water treatment following closely. Animals produce waste such as faeces, which is a major problem for farming as opposed to open ocean fishing.

Table 8.1 Traditional food sources of fat soluble vitamins: products, nutritional value (quantity, quality as % of the recommended daily intake RDI), sustainability (water and carbon footprint) and consumer acceptability (price, sensory)

	Nutrition		Sustainability		Acceptability	
Food products	Quantity (per 100 g)	Quality (%RDI)	Water Footprint (L water/kg product)	Carbon Footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory Profile
Vitamin A						
Beef liver	7.7 mg NIH (2021a)	860% NIH (2021a)	15,712 Gerbens-Leenes et al (2014)	18–25 Buratti et al. (2017)	1.7 New Zealand Fresh (2021)	Tender, juicy, bitter, iron, acidulous Wiklund et al. (2003)
Carrots	0.36 mg NIH (2021a)	40% NIH (2021a)	195 Mekonnen and Hoekstra (2011)	0.11–0.31 Röös and Karlsson (2013)	0.25 Countdown (2021)	Orange, earthy, sweet Condurso et al. (2020)
Vitamin D						
Trout	19 μg NIH (2021b)	95% NIH (2021b)	20 Pérez-Rincón et al. (2017)	4–15 Liu et al. (2016)	3.7 (salmon) Countdown (2021)	Fatty, fishy Sealey et al. (2011)
Milk	1.2 μg NIH (2021b)	6% NIH (2011b)	2872–7645 Ibidhi et al (2020)	1.0–1.5 Flysjö et al. (2011) Poore and Nemecek (2018)	0.18 Countdown (2021)	White, creamy, sweet Frøst et al. (2001)
Vitamin E						
Almonds	24 mg NIH (2021c)	159% NIH (2021c)	10,000–12,000 Fulton et al. (2019)	1.9 Marvinney and Kendall (2021)	0.27 Countdown (2021)	Sweet, astringent Franklin and Mitchell (2019)
Sunflower Oil	40 mg NIH (2021c)	264% NIH (2021c)	6,792 Mekonnen and Hoekstra (2011)	0.76 Schmidt (2015)	0.35 Countdown (2021)	Sunflower seeds, nutty Bendini et al. (2011)
Vitamin K						
Spinach	0.48 mg NIH (2021d)	403% NIH (2021d)	292 Mekonnen and Hoekstra (2011)	0.50 Seo et al. (2017)	0.40 Countdown (2021)	Bitter, hard, rough, juicy Neal et al. (2010)
Kale	0.38 mg NIH (2021d)	313% NIH (2021d)	322 HEALabel (2021)	0.40 Yuttitham (2019)	2.0 Countdown (2021)	Bitter, hard, fibrous Armesto et al. (2016)

Therefore treatment of the wastewater is needed to prevent eutrophication, which involves unwanted algae growth with toxic effects on local fish and plants. Simultaneously, open ocean fishing involves fuel consumption, thus carbon emissions (Tan & Culaba, 2009).

From a consumer point of view, fatty fish is often quite expensive, as much as 16 times more than milk (Countdown, 2021) thus limiting its consumption. Taste wise, while milk is more neutral (sweet, creamy, with white appearance), trout has a distinct smell which can be overcome by smoking, and it delivers a fatty texture (Frøst et al., 2001; Sealey et al., 2011).

8.2.3 Vitamin E

Oilseeds and nuts are excellent sources of tocopherol and tocotrienol (Vitamin E). For example, 100 grams of almonds deliver 159% of the RDI (NIH, 2021c), meaning that about 60 grams of almonds are enough to cover the daily need. Similarly, 40 ml of sunflower oil deliver the RDI of vitamin A, containing 40 mg per 100 ml (NIH, 2021c).

Environmentally, the picture is less shiny. Nuts like almonds require large volumes of water for irrigation in warm climates, with a water footprint that reaches 10,000–12,000 L/kg (Fulton et al., 2019). This coupled with a moderate carbon emission of 1.9 kg CO_2 mostly due to harvesting and packaging (Marvinney & Kendall, 2021). On the contrary, oilseeds have lesser impact, although relevant. For example, sunflower oil production calls for about 7,000 L of water (Mekonnen & Hoekstra, 2011) and emits 0.76 kg CO_2 (Schmidt, 2015). Seeds require less water to be grown and only oil extraction requires energy and processing in significant amounts, more than seeds harvesting. This advantage is particularly evident for sunflower as opposed to other oilseeds such as palm, soybean, rapeseed and peanut, which are more demanding in terms of water (Schmidt, 2015).

Price wise, both sources are extremely cheap, being sold at around 0.30 NZD/100 g (Countdown, 2021). Taste is subjective, but in both cases the high amounts of fibre and fat confer hard crunchy texture and nutty notes (Bendini et al., 2011; Franklin and Mitchell, 2019).

8.2.4 Vitamin K

Green leafy vegetables are a powerhouse for vitamin K. As little as 25–30 grams of spinach and kale, respectively, contain enough vitamin K to cover the RDI. Spinach, in particular, contain 0.48 mg/100 g equivalent to 403% of the RDI (NIH, 2021d).

Environmentally, these vegetables have a limited impact. Around 300 L of water are required per kg of vegetable (HEALabel, 2021; Mekonnen & Hoekstra, 2011). Similarly, only 0.50 kg CO_2 are emitted by the farming and harvesting of spinach and kale (Seo et al., 2017; Yuttitham, 2019).

Price wise, a difference is evident. Kale is 5 times more expensive than spinach: 2.0 vs. 0.40 NZD/kg (Countdown, 2021). This was attributed to the ubiquity of spinach in terms of geographical location. Taste wise, both spinach and kale are hard, juicy and rough. Nonetheless, kale present more sensory challenges due to its harder fibrous texture (Armesto et al., 2016; Neal et al., 2010).

8.3 Innovative Food Sources of Fat Soluble Vitamins

8.3.1 Vitamin A

Beef liver has sustainability and sensory issues. Carrots have limited sensory appeal while delivering lower vitamin A content. Therefore, innovations are welcome. Sweet potatoes contain high levels of vitamin A, mostly in the form of β-carotene (Oloniyo et al., 2021). The combination of nutritional value, sweet flavour and juicy texture, projects sweet potatoes as a valuable bakery ingredient. When used as flour, it delivered high levels of β-carotene: 15–39 mg/100 g in the dough and 9–18 mg/100 g in the baked bread (Oloniyo et al., 2021; Waidyarathna & Ekanayake, 2021). Sensory acceptability is high: bread, cakes and cookies have a bright yellow colour, taste sweet and juicy (Mitiku et al., 2018; Zhu & Sun, 2019). Therefore, it is expected that sweet potato flour has gained popularity as new ingredient sold in several countries. Each cultivar of sweet potato flour has a different nutritional profile. Overall, the content of vitamin A has been quantified between 5.5 and 12 mg per 100 g (Burri, 2011). This means 611–1333% RDI, literally 10 times more than the amount needed, suggesting limited consumption of this ingredient to avoid vitamin A toxicity, just like for beef liver. Unlike beef liver, the environmental impact is minimal: 383 L water needed (Mekonnen & Hoekstra, 2011), producing only 0.4 kg CO_2/kg (Xu et al., 2018). Sweet potatoes are grown in multiple countries and, like other vegetables, require few resources for harvesting and processing into flour, making an excellent solution for vitamin A: nutritionally dense, tasty and sustainable.

While orange vegetables seem an obvious source of carotenoids, dark leafy vegetables are less apparent, yet equally valuable. Spinach can cover the daily intake of vitamin A with just 100 grams. Therefore, spinach-based products can be a solution. The company Yumi's proposed a dip made based on spinach (40%) blended with oil and flavours. The presence of oil contributes to both taste and nutrition (enhancing the bioavailability of vitamin A precursor β-carotene). A 100 gram portion of this dip is estimated to deliver 84% of the RDI (NIH, 2021a; Yumi's, 2021). Similarly to sweet potatoes, the environmental footprint is extremely low: 292 L water and 0.50 kg CO_2 are the requirement (resources) and emission (due to fertilizers and food processing) (Mekonnen & Hoekstra, 2011; Seo et al., 2017).

8.3.2 Vitamin D

A source of vitamin D is fortified milk. As mentioned in Sect. 8.2.2, milk itself does not guarantee adequate levels of vitamin D. Consequently, some industries fortify it with added extracts of vitamin D, doubling its concentration to 2.3 μg/100 g, still only 12% RDI (NIH, 2021b). This, coupled with high water and carbon footprints, presents challenges.

It is not just dairy and fatty fish that contain vitamin D. Mushrooms are an excellent source. Studies have shown that mushrooms exposed to ultraviolet (UV) light such as that of sunlight contain more than 10 μg/100 g of vitamin D, meaning half of the RDI. The most common form of this nutrient found in mushrooms is vitamin D2, with lower levels of D3 (common in animals) and D4 (Cardwell et al., 2018). Fresh mushrooms contain vitamin D as well, with quantities varying greatly, from 1.0 to 58 μg/100 g of fresh weight (Cardwell et al., 2018). With this notion in mind, mushroom based food products are a great way to introduce vitamin D in our diet. One example is the mushroom patties. This product contains approximately 8% mushrooms (Food Nation, 2021). Therefore, it can be estimated that mushroom patties can deliver 5.5% of the vitamin D RDI (Food Nation, 2021; NIH, 2021b). Therefore, it is not sufficient to present them as a reliable source. Higher concentrations of mushrooms must be implemented in food formulations to fully exploit their nutritional potential. This is particularly important when looking at the incredibly low impact on the environment. Mushrooms can grow so easily, in so many substrates and climates, only require 16 litres of water (Chapagain & Orr, 2008). This is drastically lower than any other food source presented so far, 100 times lower (Tables 8.1 and 8.2). In addition, minimal carbon emission is caused by mushroom farming, 0.6–0.7 kg CO_2/kg (Hoekstra et al., 2011).

Never underestimate the role of sun: vitamin D is the only essential nutrient that can be synthesized by humans upon sun exposure. Variability takes place based on the geographical location, time of the day, age and skin pigmentation. On average, 15 min of sun exposure around noon resulted in significant vitamin D3 synthesis, doubling the blood concentration (Chalcraft et al., 2020).

8.3.3 Vitamin E

Since vitamin E is mostly found in oilseeds, it makes sense to explore these ingredients for food innovation. One of the main challenges with seeds and nuts it's the hard texture, mostly due to their fibre content and insoluble protein (Pérez-Herrera et al., 2020) coupled with bitter aftertaste due to phenolic compounds (Talcott et al., 2005). Roasting and extrusion of seeds into spreads can make them more palatable, due to smoother texture (Civille et al., 2020). Manufacturers have recently explored alternative nuts to develop novel spread: almonds, cashew nuts, and even seeds such as sunflower seeds (based on the more common sesame-based tahini). Popular products are almond butter (Pic's, 2021) and plant-based chocolate-hazelnut spread (Fix & Fogg, 2021).

Nutritionally, they perform very well, delivering respectively 41% and 179% of the RDI for hazelnut and almond spread (Fix & Fogg, 2021; NIH, 2021c; Pic's, 2021). These amounts were estimated based on the ingredient list reporting

Table 8.2 Innovative food sources of fat soluble vitamins: products, raw materials, bioavailability (quantity, quality as % of the recommended daily intake RDI) and sustainability (water and carbon footprint)

Products	Raw materials	Bioavailability	Sustainability	
		Vitamin quantity (per 100 g) and %RDI	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)
Vitamin A				
Sweet potato flour Lotus (2021)	Sweet potatoes	5.5–12 mg (611–1333%) Burri (2011), Lotus (2021)	383 Mekonnen and Hoekstra (2011)	0.40 Xu et al. (2018)
Spinach dip Yumi's (2021)	40% Spinach	0.76 mg (84%) NIH (2021a), Yumi's (2021)	292 Mekonnen and Hoekstra (2011)	0.50 Seo et al. (2017)
Vitamin D				
Mushrooms patties Food Nation (2021)	Mushrooms (8% estimated)	1.1 μg (5.5%) Food Nation (2021), NIH (2021b)	16 Chapagain and Orr (2008)	0.6–0.7 Hoekstra et al. (2011)
Fortified Milk NIH (2021)	Milk	2.3 μg (12%) NIH (2021b)	1.0–1.2 Flysjö et al. (2011)	1.0–1.2 (energy corrected) Flysjö et al. (2011)
Vitamin E				
Almond butter Pic's (2021)	Almonds	27 mg (179%) NIH (2021c), Pic's (2021)	16,095 (nuts) Mekonnen and Hoekstra (2011)	0.9–1.3 Volpe et al. (2015)
Hazelnut spread Fix & Fogg (2021)	42% Hazelnuts	6.1 mg (41%) Fix & Fogg (2021), NIH (2021c)	10,515 (nuts) Mekonnen and Hoekstra (2011)	2.6–2.8 Volpe et al. (2015)
Vitamin K				
Spinach dip Yumi's (2021)	40% Spinach	0.19 mg (161%) NIH (2021d), Yumi's (2021)	292 Mekonnen and Hoekstra (2011)	0.50 Seo et al. (2017)
Broccoli pizza crust DeIORIO's (2021)	Broccoli	N/A	285 Mekonnen and Hoekstra (2011)	1.9–3.2 (broccoli-grain products) Drewnowski et al. (2015), Górny et al. (2021)

100% almonds and 42% hazelnuts in the products. Unfortunately, the environmental impact of nuts is heavy, requiring tens of thousands litres of water (Mekonnen & Hoekstra, 2011) for irrigation and other operations. The carbon footprint is lower, interestingly more in favour of almonds than hazelnuts (about half). Seeds such as sunflower require way less water than nuts (about 3,000 vs. 10,000–15,000 L/kg) presenting a much more interesting opportunity in this sense. Nonetheless, the taste of sunflower seeds is not as appealing as that of nuts. Nuts contain less fibre and more sweet tasting carbohydrates (particularly after processing into spread) than seeds.

Sensory is a big winner for almond butter and hazelnut spread: golden/brown colour, homogeneous look, creamy texture, lightly sweet taste. Limited information is available on the sensory profile of these products. A study (Shakerardekani et al., 2013) presented it well. Roasting at 160 °C for variable time is needed to reduce water content in the nuts and develop complex flavours. This step is followed by blanching to remove the bitter hulls. Only at this stage, grinding takes place to smoothen and homogenize the texture. Unfortunately, these products can be pricey, partially due to their novelty and partially due to higher cost of the raw material (nuts vs. peanuts) (Countdown, 2021).

8.3.4 Vitamin K

Less innovation took place around vitamin K, therefore we considered products that have developed for other reasons and happen to be high in this nutrient: spinach dip and broccoli pizza crust. As for the spinach dip, the minimal environmental impact has been praised in Sect. 8.3.1. A 100 g serve of this dip is estimated to provide 161% of the RDI (NIH, 2021d, Yumi's, 2021) while tasting appealing. On the contrary, no nutritional information was found on the broccoli pizza crust. Nonetheless, it is a very interesting innovation. Broccoli contain 0.12 mg/100 g of vitamin K, covering the daily intake of this micronutrient. The amount of broccoli used in this bakery product is unknown, but it could prove to be nutritionally significant while improving taste Broccoli flour contains moderate levels of fibre (11–15 g/100 g dry weight) and high levels of soluble carbohydrates (65–72 g/100 g dry weight) thus showing potential for enhanced juiciness and elasticity, which are critical for bakery products such as pizza crust. Furthermore, the protein content of broccoli flour can reach 22 g/100 g dry weight of the dry weight, when using florets, much less (9 g/100 g dry weight) when using the stalks. Broccoli flour was shown to be highly soluble and able to absorb moisture (Campas-Baypoli et al., 2009). Protein, particularly when soluble, can improve elasticity of bakery products. Thus, further evaluation of this ingredient should be carried to fully express its potential.

8.4 Conclusions

Fat soluble vitamin are essential for human health. They can only be obtained from the diet, with the exception of vitamin D, which can be synthesised by humans upon skin exposure to sunlight. Animal sources such as beef liver and fatty fish are rich in vitamins A and D, but present environmental and economic challenges: high footprint and high price. Plant-based solutions are far more sustainable and still helpful from a nutritional standpoint. Traditional example are orange roots (carrots), nuts (almonds), seeds (sunflower) and green leafy vegetables (spinach, kale). Innovations focus on sweet potatoes, mushrooms, almonds, hazelnuts, spinach and broccoli. The most sustainable innovations propose dry vegetables as flours for nutritional benefit and superior taste. Mushrooms can enhance juiciness and umami flavour. Upcycling discarded vegetables into flours could be an excellent way to reduce waste while creating high values ingredients. This will benefit the environment (lower footprint), food manufacturers (cheaper technologies) and the consumers (nutritious, tasty and affordable foods).

References

Albahrani, A. A., & Greaves, R. F. (2016). Fat-soluble vitamins: Clinical indications and current challenges for chromatographic measurement. *The Clinical Biochemist Reviews, 37*(1), 27.

Armesto, J., Gómez-Limia, L., Carballo, J., & Martínez, S. (2016). Effects of different cooking methods on some chemical and sensory properties of Galega kale. *International Journal of Food Science & Technology, 51*(9), 2071–2080.

Bendini, A., Barbieri, S., Valli, E., Buchecker, K., Canavari, M., & Toschi, T. G. (2011). Quality evaluation of cold pressed sunflower oils by sensory and chemical analysis. *European Journal of Lipid Science and Technology, 113*(11), 1375–1384.

Buratti, C., Fantozzi, F., Barbanera, M., Lascaro, E., Chiorri, M., & Cecchini, L. (2017). Carbon footprint of conventional and organic beef production systems: An Italian case study. *Science of the Total Environment, 576*, 129–137.

Burri, B. J. (2011). Evaluating sweet potato as an intervention food to prevent vitamin a deficiency. *Comprehensive Reviews in Food Science and Food Safety, 10*(2), 118–130.

Campas-Baypoli, O. N., Sanchez-Machado, D. I., Bueno-Solano, C., Núñez-Gastélum, J. A., Reyes-Moreno, C., & Lopez-Cervantes, J. (2009). Biochemical composition and physicochemical properties of broccoli flours. *International Journal of Food Sciences and Nutrition, 60*(Supp 4), 163–173.

Cardwell, G., Bornman, J. F., James, A. P., & Black, L. J. (2018). A review of mushrooms as a potential source of dietary vitamin D. *Nutrients, 10*(10), 1498.

Chalcraft, J. R., Cardinal, L. M., Wechsler, P. J., Hollis, B. W., Gerow, K. G., Alexander, B. M., et al. (2020). Vitamin D synthesis following a single bout of sun exposure in older and younger men and women. *Nutrients, 12*(8), 2237.

Chapagain, A., & Orr, S. (2008). *UK water footprint: The impact of the UK's food and fibre consumption on global water resources volume two: Appendices* (pp. 31–33). WWF-UK.

Civille, G. V., Trail, A., Krogmann, A. R., & Thomas, E. (2020). Texture characteristics of US foods: Pioneers, protocols, and attributes-tribute to Alina. *Textural Characteristics of World Foods*, 27–36.

Condurso, C., Cincotta, F., Tripodi, G., Merlino, M., Giarratana, F., & Verzera, A. (2020). A new approach for the shelf-life definition of minimally processed carrots. *Postharvest Biology and Technology, 163*, 111138.

Countdown. (2021). https://shop.countdown.co.nz/shop/. Accessed on 23/09/2021.

DeIORIO's. (2021). https://www.deiorios.com/broccoli-pizza-dough/. Accessed on 02/11/2021.

Drewnowski, A., Rehm, C. D., Martin, A., Verger, E. O., Voinnesson, M., & Imbert, P. (2015). Energy and nutrient density of foods in relation to their carbon footprint. *The American Journal of Clinical Nutrition, 101*(1), 184–191.

Dutta, A., & Dutta, S. K. (2003). Vitamin E and its role in the prevention of atherosclerosis and carcinogenesis: a review. *Journal of the American College of Nutrition, 22*(4), 258–268.

Fix & Fogg. (2021). https://shop.fixandfogg.co.nz/products/chocolate-hazelnut-butter. Accessed on 02/11/2021.

Flysjö, A., Henriksson, M., Cederberg, C., Ledgard, S., & Englund, J. E. (2011). The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. *Agricultural Systems, 104*(6), 459–469.

Food Nation. (2021). https://foodnation.co.nz/product/happy-patties-broccoli-pea-quinoa/. Accessed on 02/11/2021.

Franklin, L. M., & Mitchell, A. E. (2019). Review of the sensory and chemical characteristics of almond (*Prunus dulcis*) flavor. *Journal of Agricultural and Food Chemistry, 67*(10), 2743–2753.

Frøst, M. B., Dijksterhuis, G., & Martens, M. (2001). Sensory perception of fat in milk. *Food Quality and Preference, 12*(5–7), 327–336.

Fulton, J., Norton, M., & Shilling, F. (2019). Water-indexed benefits and impacts of California almonds. *Ecological Indicators, 96*, 711–717.

Gerbens-Leenes, P. W., Mekonnen, M. M., & Hoekstra, A. Y. (2013). The water footprint of poultry, pork and beef: A comparative study in different countries and production systems. *Water Resources and Industry, 1*, 25–36.

Górny, K., Idaszewska, N., Sydow, Z., & Bieńczak, K. (2021). Modelling the carbon footprint of various fruit and vegetable products based on a Company's internal transport data. *Sustainability, 13*(14), 7579.

HEALabel. (2021). https://healabel.com/k-ingredients/kale. Accessed on 01/11/2021.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). *The water footprint assessment manual: Setting the global standard*. Earthscan.

Ibidhi, R., & Salem, H. B. (2020). Water footprint of livestock products and production systems: A review. *Animal Production Science, 60*(11), 1369–1380.

Liu, Y., Rosten, T. W., Henriksen, K., Hognes, E. S., Summerfelt, S., & Vinci, B. (2016). Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (Salmo salar): Land-based closed containment system in freshwater and open net pen in seawater. *Aquacultural Engineering, 71*, 1–12.

Lotus. (2021). https://www.phragos.com/lotus-sweet-potato-flour-500g/?gclid=EAIaIQobChMIodLOtoX48wIVjwByCh1kSw4PEAQYAyABEgJmY_D_BwE. Accessed on 02/11/2021.

Lucas, R. M., Gorman, S., Geldenhuys, S., & Hart, P. H. (2014). Vitamin D and immunity. *F1000prime reports, 6*.

Marvinney, E., & Kendall, A. (2021). A scalable and spatiotemporally resolved agricultural life cycle assessment of California almonds. *The International Journal of Life Cycle Assessment, 26*, 1123–1145.

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences, 15*(5), 1577–1600.

Mitiku, D. H., Abera, S., Bussa, N. and Abera, T. (2018), "Physico-chemical characteristics and sensory evaluation of wheat bread partially substituted with sweet potato (*Ipomoea batatas L.*) flour", *British Food Journal, 120*(8), 1764–1775.

Müller, D. N., Kleinewietfeld, M., & Kvakan, H. (2011). Vitamin D review. *Journal of the Renin-Angiotensin-Aldosterone System, 12*(2), 125–128.

National Research Council. (1989). *Diet and health: Implications for reducing chronic disease risk*. National Academies Press.

Neal, J. A., Booren, B., Cisneros-Zevallos, L., Miller, R. K., Lucia, L. M., Maxim, J. E., & Castillo, A. (2010). Shelf life and sensory characteristics of baby spinach subjected to electron beam irradiation. *Journal of Food Science, 75*(6), S319–S326.

New Zealand Fresh. (2021). https://newzealandfresh.sg/products/frozen-beef-liver-1kg-pack. Accessed on 23/09/2021.

NIH. Vitamin A. (2021a). https://ods.od.nih.gov/factsheets/VitaminA-HealthProfessional/. Accessed ion 17/09/2021.

NIH. Vitamin D. (2021b). https://ods.od.nih.gov/factsheets/VitaminD-HealthProfessional/. Accessed ion 17/09/2021.

NIH. Vitamin E. (2021c). https://ods.od.nih.gov/factsheets/VitaminE-HealthProfessional/. Accessed ion 17/09/2021.

NIH. Vitamin K. (2021d). https://ods.od.nih.gov/factsheets/VitaminK-HealthProfessional/. Accessed ion 17/09/2021.

Oloniyo, R. O., Omoba, O. S., Awolu, O. O., & Olagunju, A. I. (2021). Orange-fleshed sweet potatoes composite bread: A good carrier of beta (β)-carotene and antioxidant properties. *Journal of Food Biochemistry, 45*(3), e13423.

Olson, J. M., Ameer, M. A., & Goyal, A. (2021). *Vitamin A toxicity*. StatPearls [Internet]..

Pérez-Herrera, A., Martínez-Gutiérrez, G. A., León-Martínez, F. M., & Sánchez-Medina, M. A. (2020). The effect of the presence of seeds on the nutraceutical, sensory and rheological properties of Physalis spp. fruits jam: A comparative analysis. *Food Chemistry, 302*, 125141.

Pérez-Rincón, M. A., Hurtado, I. C., Restrepo, S., Bonilla, S. P., Calderón, H., & Ramírez, A. (2017). Water footprint messure method for tilapia, cachama and trout production: Study cases to Valle del Cauca (Colombia). *Ingeniería y Competitividad, 19*(2), 115–126.

Pic's. (2021). https://www.picspeanutbutter.com/pics-peanut-butter-products/spreads-its-what-we-do/peanut-butter-5/. Accessed on 02/11/2021.

Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science, 360*(6392), 987–992.

Röös, E., & Karlsson, H. (2013). Effect of eating seasonal on the carbon footprint of Swedish vegetable consumption. *Journal of Cleaner Production, 59*, 63–72.

Schmidt, J. H. (2015). Life cycle assessment of five vegetable oils. *Journal of Cleaner Production, 87*, 130–138.

Sealey, W. M., Gaylord, T. G., Barrows, F. T., Tomberlin, J. K., McGuire, M. A., Ross, C., & St-Hilaire, S. (2011). Sensory analysis of rainbow trout, *Oncorhynchus mykiss*, fed enriched black soldier fly prepupae, *Hermetia illucens*. *Journal of the World Aquaculture Society, 42*(1), 34–45.

Seo, Y., Ide, K., Kitahata, N., Kuchitsu, K., & Dowaki, K. (2017). Environmental impact and nutritional improvement of elevated CO2 treatment: A case study of spinach production. *Sustainability, 9*(10), 1854.

Shakerardekani, A., Karim, R., Ghazali, H. M., & Chin, N. L. (2013). Textural, rheological and sensory properties and oxidative stability of nut spreads—A review. *International Journal of Molecular Sciences, 14*(2), 4223–4241.

Stacchiotti, V., Rezzi, S., Eggersdorfer, M., & Galli, F. (2021). Metabolic and functional interplay between gut microbiota and fat-soluble vitamins. *Critical Reviews in Food Science and Nutrition, 61*(19), 3211–3232.

Talcott, S. T., Passeretti, S., Duncan, C. E., & Gorbet, D. W. (2005). Polyphenolic content and sensory properties of normal and high oleic acid peanuts. *Food Chemistry, 90*(3), 379–388.

Tan, R. R., & Culaba, A. B. (2009). Estimating the carbon footprint of tuna fisheries. *WWWF Binary Item, 17870*, 14 pages.

Vermeer, C. V. (2012). Vitamin K: The effect on health beyond coagulation–an overview. *Food & Nutrition Research, 56*(1), 5329.

Volpe, R., Messineo, S., Volpe, M., & Messineo, A. (2015). Carbon footprint of tree nuts based consumer products. *Sustainability, 7*(11), 14917–14934.

Waidyarathna, G. N. N., & Ekanayake, S. (2021). Nutrient composition and functional properties: Suitability of flour of sweet potatoes (Ipomea batatas) for incorporation into food production. *International Journal of Biological and Chemical Sciences, 15*(3), 897–908.

Wiklund, E., Johansson, L., & Malmfors, G. (2003). Sensory meat quality, ultimate pH values, blood parameters and carcass characteristics in reindeer (Rangifer tarandus tarandus L.) grazed on natural pastures or fed a commercial feed mixture. *Food Quality and Preference, 14*(7), 573–581.

Wiseman, E. M., Bar-El Dadon, S., & Reifen, R. (2017). The vicious cycle of vitamin a deficiency: A review. *Critical Reviews in Food Science and Nutrition, 57*(17), 3703–3714.

Xu, Z., Xu, W., Peng, Z., Yang, Q., & Zhang, Z. (2018). Effects of different functional units on carbon footprint values of different carbohydrate-rich foods in China. *Journal of Cleaner Production, 198*, 907–916.

Yumi's. (2021). https://yumis.com.au/products/classic-dip/creamed-spinach-dip/. Accessed on 02/11/2021.

Yuttitham, M. (2019). Comparison of carbon footprint of organic and conventional farming of Chinese kale. *Environment and Natural Resources Journal, 17*(1), 78–92.

Zhu, F., & Sun, J. (2019). Physicochemical and sensory properties of steamed bread fortified with purple sweet potato flour. *Food Bioscience, 30*, 100411.

9

Bioactive Compounds from Food and Their Applications in the Treatment of Type 2 Diabetes

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Abstract

The occurrence of insulin and glucose metabolism disorders (collectively referred to as Diabetes), are increasing globally with expectations that over 700 million individuals will be diagnosed with Type 2 Diabetes by 2025. Current treatments for Type 2 Diabetes are limited by the side effects they impose on patients as well as the practical ability to resolve all aspects of the illness. Therefore, there is a need to develop new treatment approaches. Bioactive compounds derived from foods including, phenolic compounds, alkaloids, and bioactive peptides, have been shown to have potential as treatments for Type 2 Diabetes. Mechanisms of action for bioactive compounds derived from foods against Type 2 Diabetes include α-amylase and α-glucosidase inhibition, incretin hormone modulation, and modulation of insulin receptors (both expression and sensitivity). Before there use, bioactive compounds require concentration, extraction, and (or) purification from the original source. The protein fraction of food waste, especially animal-based foods, can also be used as a substrate for the generation of bioactive peptides or as a source of enzymes that can be subsequently used for the generation of bioactive peptides. Waste derived from plant based food systems, is known to be especially rich in phenolic compounds and alkaloids. When extracted using modern processing methods such as microwave assisted extraction or Pulsed electric field, plant based food waste can be seen as a sustainable source of these compounds. This chapter explores selected bioactive compounds found in food and evaluates them in the context of the treatment of Type 2 Diabetes.

Keywords

Bioactive peptides, Non-peptide bioactives, Type 2 diabetes, Phenolic, Alkaloid

Abbreviations

DPPH	2,2-diphenyl-1-picrylhydrazyl radical scavenging capacity
ORAC	oxygen radical absorbance capacity
PEF	pulsed electric field
HPLC	high-performance liquid chromatography
UPLC	ultra-performance liquid chromatography

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Da	Dalton
GLP-1	glucagon-like peptide-1
GIP	gastric inhibitory polypeptide
DPP-IV	Dipeptidyl peptidase-IV

9.1 Introduction

The main reason for the consumption of food is to provide the core nutrients required for energy, body maintenance, and normal physiological function. These essential nutrients are proteins, lipids, carbohydrates, vitamins, and minerals (Ellwood et al., 2014). A secondary aspect driving food consumption is the effects that components other than the essential nutrients can have on consumer health and wellbeing. Of particular note are low abundance compounds within food including alkaloids, phenolic compounds, and peptides (Recharla et al., 2017). In the context of food, these low abundance compounds are referred to as bioactive compounds (Recharla et al., 2017). Classically, any compound that interacts with the metabolism and (through that interaction) results in at least one physiological response is considered bioactive (or a bioactive compound) (Dima et al., 2020; Fernández-García et al., 2009). According to the above general definition, both the essential nutrients and low abundance compounds can be considered bioactive. To differentiate these within the context of food the term bioactive (or bioactive compound) is specifically used to refer to low abundance compounds that have been linked to a physiological response (Recharla et al., 2017). These responses can include (but are not limited to) antioxidant activity, antimicrobial activity, anti-inflammatory activity, anti-diabetic functions, and cholesterol lowering activity (Ellwood et al., 2014).

Type 2 Diabetes (also known as Diabetes Mellitus) is an autoimmune disease estimated to affect over 400 million people worldwide (Patil et al., 2020). Type 2 Diabetes is one of a wider set of conditions and disorders associated with insulin and glucose metabolism collectively referred to as Diabetes. The characteristic pathology of Type 2 Diabetes is the reduced production of insulin or insufficient insulin response, identified formally as insulin resistance. This can be contrasted with Type 1 Diabetes (also known as Juvenile Diabetes) where natural pancreatic insulin secretion is essentially non-existent (Patil et al., 2020). All forms of Diabetes are considered heterogeneous metabolic syndromes and are driven by a combination of lifestyle and genetic factors (Tuomi et al., 2014; Unuofin & Lebelo, 2020). The impacts of Type 2 Diabetes are hard to classify in interval patients. However, Type 2 Diabetes has been associated with a range of undesirable long-term effects including weight loss or gain, chronic hypertension, cardiovascular damage, nerve damage, kidney damage, optic damage, and neurodegeneration (Tuomi et al., 2014).

It is expected that by 2025 over 700 million people will be diagnosed with Type 2 Diabetes (Tuomi et al., 2014). This sharp rise in cases is predicted to result in a large burden on the medical system and be correlated with extremely high medical costs (van Dieren et al., 2010). Of particular note is the limited effectiveness of treatment options currently available. A number of pharmaceutical options are available for Type 2 Diabetes treatment, including dipeptidyl peptidase-4 (DPP-IV) inhibitors, glucagon-like peptide-1 (GLP-1) agonists, sodium-glucose cotransporter (SGLT2) inhibitors, and insulin injections. However, each of these has associated side effects, and limited effectiveness (Chaudhury et al., 2017). One key application for bioactive compounds derived from food is both direct treatment and management of Type 2 Diabetes (Yan et al., 2019).

9.2 Types of Bioactive Compounds

Typically, bioactive compounds are classified based on either their functionality or chemical characteristics. The classification based on chemical characteristics (e.g. structure and molecular weight) is considered important to allow for the identification and purification of bioactive compounds (Azmir et al., 2013; Laraia et al., 2018). A focus on functionality is important in the context of evaluating the potential applications of a compound (Dima et al., 2020). It must be noted that wide chemical and structurally diversity has been identified between compounds that share the same types of bioactive functions. Simultaneously, any given bioactive compound may also carry out multiple functions. This means it is difficult to predict and quantify the functionality of a compound. In contrast methods including (but not limited to) Nuclear Magnetic Resonance (NMR), Fourier-transform infrared spectroscopy (FT-IR), Mass spectrometry, and Chromatography techniques allow for accurate structural determination (Ingle et al., 2017).

9.2.1 Common Classes of Non-peptide Bioactives

9.2.1.1 Phenolic Compounds

Phenolic compounds are a large group of related compounds that contain at least one aromatic ring. Phenolic compounds are commonly found in plant tissues acting as secondary metabolites (Albuquerque et al., 2021). Common examples of phenolic compounds include gallic acid, caffeic acid, and catechin (Figure 9.1). Key subcategories of phenolic compounds include phenolic acids, flavonoids (including anthocyanins), and tannins (Sagar et al., 2018). The consumption of phenolic compounds has been linked to a range of positive health outcomes including acting against Alzheimer's disease, cancers, obesity, and diabetes (Caleja et al., 2017; Haminiuk et al., 2012).

Due to the presence of conjugated bonds and ring structures (Figure 9.1), a large proportion of phenolic compounds are able to act as antioxidants (Albuquerque et al., 2021). The antioxidant capacity of a phenolic compound is dependent firstly on the structure of the phenolic compound, and secondly, the specific method used to evaluate the antioxidant capacity. For example, the antioxidant activity of catechin is 0.8 mmol Trolox/mmol and 7.9 mmol Trolox/mmol, when measured by the 2,2-diphenyl-1-picrylhydrazyl radical scavenging capacity (DPPH) and oxygen radical absorbance capacity (ORAC), respectively (Tabart et al., 2009). The evaluation of antioxidant capacity in isolation has however been widely criticised. This critique is associated with both the large variation in methods available to antioxidant capacity and the non-specific nature of these methods (Harnly, 2017).

Within the metabolism of plants, phenolic compounds play a variety of roles most notably

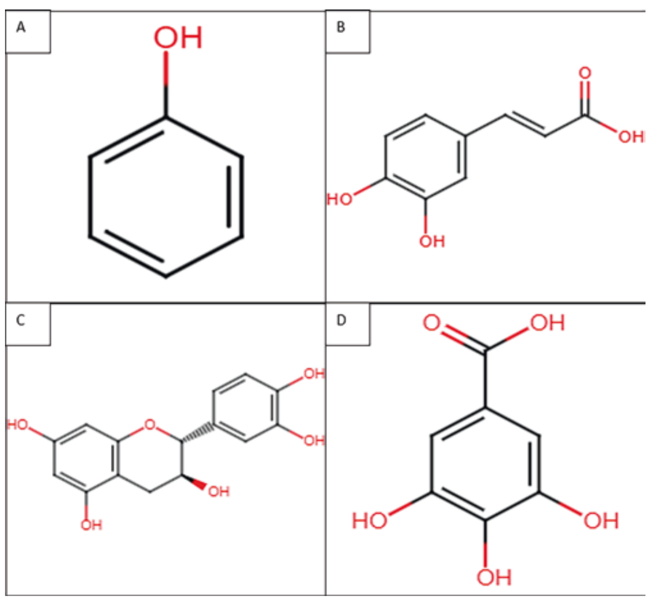

Fig. 9.1 A, B, C, and D: Chemical structures of common phenolic compounds: basic phenol structure (a), caffeic acid (b), catechin (c), and gallic acid (d)

acting as pigments, UV protective agents, and anti-parasitic agents. Many of these functions are predicated on the phenolic compounds present in surface tissues (cuticle), berries, fruits, and flours (Albuquerque et al., 2021). In addition to the above functions within the context of food, Phenolic compounds also act as tastants. Higher molecular weight poly-phenolic compounds like tannins can also provide additional astringent characteristics to beverages especially red wines (Dias Araujo et al., 2021).

9.2.1.2 Alkaloids

Alkaloids are an extremely heterogeneous group of compounds characterised only by the presence of at least one nitrogen within the structure and an inability to be classified into a more common group (e.g. amines) (Figure 9.2). Though present in all living systems, alkaloids commonly found in both plant and fungal tissues show high levels of bioactivity (Dey et al., 2020).

From a pharmaceutical and medical perspective, alkaloids are extremely common with functions including analgesics, antihypertensives, and antiarrhythmics. Examples of classical medications that have alkaloid structures include morphine, codeine, and quinine (Dey et al., 2020). Additionally, alkaloid structures are common in recreational drugs acting as stimulants, analgesics, and hallucinogens. Examples range from the more common caffeine and nicotine to illicit drugs such as cocaine and psilocybin (Matsuura & Fett-Neto, 2015; Reyes & Cornelis, 2018).

Alkaloids in the food chain have been traditionally associated with toxic and harmful effects. Damage to the liver resulting in a range of hepatic disorders has been generally associated with toxic alkaloids. Additional effects of toxic alkaloids include (but are not limited to) cardiovascular disorders, convulsions, and gastro-intestinal disruption (Caradus et al., 2022; Dusemund et al., 2018). The most well describe group of toxic alkaloids are associated with fungi, specifically the ergot fungi and the wider *Claviceps* genus (Klotz, 2022). Over 80 toxic compounds of different classifications have been associated with the *Claviceps* genus almost all of these compounds are considered mycotoxins (Caradus et al., 2022). Ergot fungi can grow on a range of different cereal and grass substrates and the associated toxins are easily transmitted through the food chain both directly to humans and stock animals like cattle, sheep, and pigs (Caradus et al., 2022).

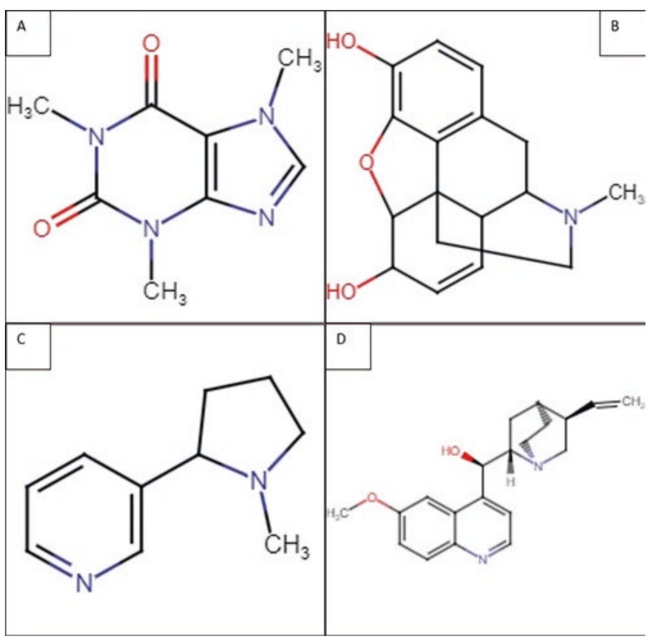

Fig. 9.2 A, B, C, and D: Chemical structures of common alkaloids: caffeine (a), morphine (b), nicotine (c), and quinine (d)

Not all alkaloids in food are harmful. As this is such a large and diverse ground of compounds. As already indicated caffeine, found in many plant derived food including tea and coffee is an alkaloid. The bitterness associated with caffeine is also a good example of the impact alkaloids can have on the sensory perception of foods (Reyes & Cornelis, 2018). Quinine, the characteristic component of tonic water is also associated with a bitter flavour. Traditionally quinine used to prepare tonic water was extracted from the cinchona tree, though now in many cases synthetic quinine is used (Misra et al., 2008). Modern tonic water is reported to contain around 80 mg L^{-1}, though historical reports indicate substantially higher levels have been used (Donovan et al., 2003).

9.2.1.3 Concentration, Extraction, and Purification of Non-peptide Bioactives

Non-peptide bioactives are present in biological tissues at low and extremely variable concentrations. This presents a key challenge in their applications both as food ingredients and as pharmaceutical agents (Bubalo et al., 2018). For example, bark from the cinchona tree *(Cinchona spp.)* has been shown to have concentrations of the alkaloid quinine ranging from 0.2 to 25.8 mg g^{-1} (Maldonado et al., 2017). A number of approaches have been used to overcome the problem of low concentrations. Solvent extraction has traditionally been used especially for non-polar compounds (Ingle et al., 2017). Solvent extraction methods have been criticised due to the use of toxic agents and the generation of large volumes of environmentally hazardous by-products (Bubalo et al., 2018; Gullón et al., 2020). Of particular concern is the use of chloroalkanes including dichloromethane (CH_2Cl_2) and chloroform ($CHCl_3$) (Capello et al., 2009). The use of modern methods of extraction has somewhat overcome these concerns. The development of alternative solvents including deep eutectic solvents such as has been able to provide alternatives to chloroalkanes (Zainal-Abidin et al., 2017). In addition, the use of methods to improve extraction efficacy has allowed for the reduction in solvent volumes and increased extraction yields. The commonly applied methods include, microwave assisted extraction, pulsed electric field (PEF), and ultrasound assisted extraction (Giacometti et al., 2018).

To establish the bioactive functionality of a given compound purification is required. This is because of the potential interference of other compounds within complex biological systems. The ability to obtain pure compounds is a core aspect of the wider ethnopharmacological approach whereby the traditional knowledge associated with medicinal plants is evaluated using analytical methods (Brusotti et al., 2014). Solvent based extraction methods (as identified above) do carry out partial purification. These methods are however, limited in their ability to separate compounds with similar chemical characteristics, epically hydrophobicity. The use of chromatographic methods including high-performance liquid chromatography (HPLC) and ultra-performance liquid chromatography (UPLC) have been critical to overcoming the limitations of basic extraction methods (Ingle et al., 2017).

The development of chemically synthesised analogues of non-peptide bioactives is an approach that has been applied particularly in the context of pharmaceutical applications. The classical example of this is the non-steroidal anti-inflammatory acetylsalicylic acid, also known as aspirin. The use of plants containing aspirin has been traced back as far as 1534 BCE to treat inflammatory rheumatic diseases (Montinari et al., 2019). Between the 1820's and 1890's a number of critical developments occurred that culminated in Felix Hoffmann and Arthur Eichengrün synthesising aspirin for later commercialisation by the Bayer Corporation (Fuster & Sweeny, 2011; Montinari et al., 2019). The use of synthesised analogues of non-peptide bioactives overcomes the problems associated with low concentrations and some concerns associated with purification. However, synthesis is not possible for all compounds especially higher molecular weight compounds such as tannins (Albuquerque et al., 2021).

Waste streams from food production can provide an alternative source of low cost bioactive compounds without the need to conduct complex chemical synthesis. For example, the peel from citrus fruits (*Citrus* spp.) can make up between 5 and 40% of the total fruit weight (Mahato et al., 2019). During food, processing citrus peel is normally actively separated from the desirable flesh and discarded. However, a range of non-peptide bioactive compounds can be extracted from the peels including the polyphenols ferulic acid, p-hydroxybenzaldoxime, p-cinnamic acid and isoferulic acid, and vanillic acid. The skins of a range of other plants including potatoes (*Solanum tuberosum*), cucumbers (*Cucumis sativu*), and tomatoes (*Solanum lycopersicum*) have also been identified as rich sources of non-peptide bioactives (Sagar et al., 2018).

9.2.2 Bioactive Peptides

Peptides are generally defined as chains of amino acids that are between 2 and 20 residues long (with a molecular mass of up to 600 Da) (Sarmadi & Ismail, 2010). These chains can have dual functions as nutritional sources of amino acids and as bioactive compounds (Karami & Akbari-Adergani, 2019). Commonly cited functions of bioactive peptides include (but are not limited to) antihypertensive activity, hypocholesterolemic activity, antimicrobial activity, immunomodulatory activity, anti-oxidant activity, and cytomodultory activity (Karami & Akbari-Adergani, 2019; Korhonen & Pihlanto, 2006). Not all bioactive functions performed by peptides are considered positive. For example, β-casomorphins, and specifically β-casomorphin-7, have been alleged to act in an inflammatory manner within the gastrointestinal system (Kay et al., 2021). In addition, the individual functions of bioactive peptides are not mutually exclusive. For example, Minervini et al. (2003) identified that the peptide sequence Tyr-Phe-Tyr-Pro-Glu-Leu from αs1-casein showed angiotensin-converting enzyme inhibitory activity and antioxidant activity (as measured by ORAC assay).

Peptides can be generated in biological systems during the break down of larger proteins (both chemical and enzymatic). Within the context of food peptide generation from proteins occurs at a number of stages including processing, storage, and gastrointestinal digestion (Ryder et al., 2016; Toldrá et al., 2018). The intentional generation of peptides using enzymatic hydrolysis of proteins has also been of increasing focus within the literature. As identified in Table 9.1 protease sources used for the intentional generation of peptides can include animals, plants, bacteria, and fungi (Toldrá et al., 2018). The identification of enzymes with protease activity in waste streams associated with food is one area of large potential. Proteases derived from waste streams can have unique hydrolysis characteristics including substrate specificity, wide catalytic temperatures, and wide functional pH ranges. For example, Espósito et al. (2009) purified alkaline proteases from the viscera of the Tambaqui fish (*Colossoma macropomum*). The purified proteases showed optimum activity within a pH range of 10–12 and at a temperature of 60 °C. Proteases can also be derived indirectly from waste streams, most commonly by isolating and characterising protease producing bacteria with novel properties. The most commonly targeted waste streams are high protein, low carbohydrate waste streams found in animal processing. The extent of purification has varied with Ramakodi et al. (2020) isolating the proteolytic bacteria *Chromobacterium violaceum* from slaughterhouse effluent samples without characterising the specific proteolytic enzymes. In contrast, Anandharaj et al. (2016) purified and characterised a metallo-protease from *Bacillus alkalitelluris* TWI3 that originated in tannery waste. Due to the large number of proteolytic options available, the combination of protease(s) with proteins substrates is, therefore, a critical consideration.

When considering the generation of peptides the amino acid sequence of the protein substrate present and the concentration of those proteins need to be considered. The amino acid sequence of the proteins present is important as it determines the potential peptides that can be liberated. The protein profile and subsequent amino acid

Table 9.1 A selection of enzymes used to generate bioactive peptides

Enzyme source		Enzyme name	Enzyme classification	Citation
Biological kingdom	Derivation			
Animal	Waste streams	*Colossoma macropomum* protease	Alkaline protease	Espósito et al. (2009)
	Gastro-intestinal system	Pepsin	Aspartic endopeptidase	Lo et al. (2016) and Ryder et al. (2016)
		Trypsin	Serine endopeptidase	
		Chymotrypsin		
Bacterial	Commercial preparation	Alcalase (2.4 L)[a]	Alkaline endopeptidase	Toldrá et al. (2018)
			Amino peptidase	
			Metalloprotease (neutral)	
		Flavourcyme (1000M)[a]	Amino-peptidase	
			Endopeptidase	
		Prolidase	Dipeptidase	
		Valkerase[a]	Endopeptidase	
		Neutrase[a]	Metalloprotease	
	Waste streams	*Bacillus alkalitelluris* TWI3 protease		Anandharaj et al. (2016)
Fungal	Commercial preparation	Acidic fungal protease	Acidic protease	Ryder et al. (2016)
		Fungal protease 31,000	Protease (un-specified)	
		Fungal protease II		
		Fungal protease 60,000		
		HT proteolytic protease		
Plant	Tissue	Actinidin	Cysteine endopeptidase	Ha et al. (2012)
		Papain		
		Bromelain		
		Zingibain		

[a] indicates enzyme mixtures

sequence can also be used as a key tool to screen the potential of proteins to act as peptide substrates, this emerging methodology is often referred to as a bioinformatics approach (Udenigwe, 2014) or peptidomics (Sánchez-Rivera et al., 2014). The experimental validation of the function of peptides identified using a bioinformatics approach is required but the time needed is less than the traditional empirical methods (Udenigwe, 2014). In turn, the concentration of the proteins present within a food determines the efficacy of the overall process and plays a key role in determining process yield (Görgüç et al., 2020). In addition to peptides that are generated enzymatically, native peptides with bioactivity have also been identified within both plant and animal sources (Cerrato et al., 2021; Görgüç et al., 2020).

Food components, both protein and non-protein, have the direct ability to interfere with the generation of bioactive peptides. Protease inhibitors act at low concentrations to prevent the action of proteolytic enzymes. Most protease inhibitors also show specificity towards individual protease enzymes. Proteases inhibitors are present at notably higher concentrations in plant tissues than in animal tissues (Hellinger & Gruber, 2019). The role of protease inhibitors in plant systems is varied and includes metabolic regulation, protection against pests and protection, against pathogens (Ryan, 1990). The presence of protease inhibitors has historically been a concern with respect to the nutritional value of plant protein due to the ability of inhibitors to reduce the efficiency of gastrointestinal digestion (Samtiya et al., 2020). Given that, proteases act both as a part of the gastrointestinal digestion process and as a key facilitator in the formation of bioactive peptides, this concern is relevant to the production of peptides.

9.3 Treatment and Management of Type 2 Diabetes

The primary treatment prescribed for Type 2 Diabetes is insulin injections administered after food consumption (post-prandial) to increase serum insulin levels. The increased circulating insulin stimulates the uptake of glucose from the blood into cells of the muscle, fat, and brain. This results in a reduction of blood glucose, which ameliorates the risk of hyperglycaemia and peripheral insulin resistance typical in Type 2 Diabetes (Chaudhury et al., 2017). Insulin injections only treat one aspect of Type 2 Diabetes and the key symptoms of the condition. Medications including α-glucosidase inhibitors and inhibitors of DPP-IV are commonly prescribed alongside insulin injections to target the underlying systematic drivers of Type 2 Diabetes (Table 9.2) (Casey et al., 2021; Seino et al., 2010).

Each of the commonly prescribed medications currently used to treat Type 2 Diabetes (Table 9.2) has been associated with side effects. Commonly accepted side effects include nausea, stomach pains, headaches, dizziness, weight gain, hypersensitivity, and toxicity (Chaudhury et al., 2017). These side effects can directly affect the willingness of Type 2 Diabetes patients to adhere to medication regimes (Rezaei et al., 2019). Even when taken as prescribed these medications can have limited abilities to manage Type 2 Diabetes in all cases (Casey et al., 2021; Seino et al., 2010). Bioactive compounds derived from food provide a natural and accessible alternative to Type 2 Diabetes medications with minimal side effects (Jakubczyk et al., 2020).

Table 9.2 Common medications used to treat and control Type 2 Diabetes (Adapted from Chaudhury et al. (2017) and National Center for Biotechnology XE "Biotechnology" Information (2022))

Mechanism of action	Common name	Compound type
α-glucosidase inhibition	Acarbose	Iminosaccharide
	Voglibose	
	Miglitol	Alkaloid
DPP-IV inhibition	Alogliptin	
	Sitagliptin	β-amino acid derivative
	Saxagliptin	Dipeptides derivative
	Vidagliptin	Nitrile derivative
	Linagliptin	Purine
	Exenatide	Peptide

9.3.1 Inhibitors of Carbohydrate Digestion and Absorption

Targeting carbohydrate digestion and absorption is one key mechanism for the management of Type 2 Diabetes. This includes targeting enzymes that control the degradation of starch, into Mono and Di- saccharides (Abdelli et al., 2021). Inhibiting the activity of these enzymes has the effect of preventing spikes in post-prandial blood glucose levels (González-Montoya et al., 2018; Patil et al., 2020). α-amylase and α-glucosidase are two key enzymes in the process of carbohydrate digestion and absorption. α-amylase is a glycoside hydrolase enzyme that catalyses the hydrolysis of the $\alpha_{1\rightarrow4}$-glycosidic bonds of complex polysaccharides into oligosaccharides. α-amylase is secreted from the salivary glands and pancreas after consumption of carbohydrates. In contrast, α-glucosidases are a group of enzymes secreted in the intestine to break down polysaccharides into glucose. Though both α-amylase and α-glucosidases catalyses the hydrolytic cleavage of the $\alpha_{1\rightarrow4}$-glycosidic bonds α-glucosidases targets terminal bonds (Ramasubbu et al., 1996).

Bioactive peptides have been shown to act as α-amylase and α-glucosidases inhibitors. Several *in vitro* studies report the efficacy of plant, egg, and dairy derived mixtures of bioactive peptides (hydrolysates) in the inhibition of both α-amylase and α-glucosidase (González-Montoya et al., 2018; Jan et al., 2016; Yu et al., 2012). Peptides with α-amylase and α-glucosidase inhibition activity are commonly short, with molecular weights of between 1 and 5 kDa (Jakubczyk et al., 2020). It has been suggested that key amino acid residues commonly present in bioactive peptides with α-amylase inhibition functions are Histidine, Methionine, and Proline. This is believed to be because the catalytic regions of α-amylase favours hydrophobic and hydrogen bonding interactions when binding substrates (Jakubczyk et al., 2020). The preferential structural features of α-glucosidase inhibitors are suggested to include amino terminal residues with hydroxyl side chains including Serine, Threonine, Tyrosine, Proline, Alanine, and Methionine (González-Montoya et al., 2018). As there is substantial overlap between the binding preferences for both α-amylase and α-glucosidase, peptides identified as having inhibitory activity against one enzyme will commonly have an inhibitory activity on the other. Food derived bioactive peptides with α-amylase and α-glucosidase inhibition activity tend to be derived from plant based protein sources, this includes from walnuts (*Juglans regia*), soybean (*Glycine max*), and oat (*Avena sativa*) (Fuentes et al., 2021; González-Montoya et al., 2018; Wang et al., 2020).

A range of phenolic compounds have been associated with α-amylase and α-glucosidase inhibition. Of particular note are the flavonoids and specifically anthocyanins. Grapes (*Vitis vinifera*), soybeans (*Glycine max*), figs (*Ficus carica*), and the citrus family (*Citrus* spp.) have all been identified as key sources of α-amylase and α-glucosidase inhibitory anthocyanins (Gaikwad et al., 2014). However, as phenolic compounds are widely dispersed in plants and especially concentrated in fruits it is believed that this is just a small selection of the food products that will contain α-amylase and α-glucosidase inhibitory anthocyanins (Les et al., 2021). Work establishing the mechanism behind the inhibition of α-amylase by anthocyanins has indicated that binding to the glutamic acid residue at position 233 is critical for inhibition (Ji et al., 2021). It is not clear at this stage how this translates to α-glucosidase inhibition.

A large number of plant-derived alkaloids have shown great potential as both α-amylase and α-glucosidases inhibitors. Over 30 different alkaloids from plants with α-amylase and α-glucosidases inhibitory effects have been identified (Yin et al., 2014). Structural similarities of some alkaloid sub-groups and the structure of amino acids in α-amylase and α-glucosidases inhibitory peptides have been identified. For example, tyrosine and the benzylisoquinoline and iso-quinoline alkaloid groups (Rasouli et al., 2020). Though not all alkaloid compounds have sutural similarities with amino acids, it is believed that analogues binding interactions may occur.

A number of established drugs that target and inhibit the α-amylase and α-glucosidases enzymes are alkaloids, this includes Miglitol (Table 9.2) (Chaudhury et al., 2017). In the context of plants used for food production, the *Moraceae* family has been identified as a key source of α-amylase and α-glucosidases inhibitory alkaloids (Yin et al., 2014). The *Moraceae* family includes mulberries (*Morus rubra* and *Morus alba*), figs (*Ficus carica*), and jackfruit (*Artocarpus heterophyllus*) (Somashekhar et al., 2013). However, because the *Moraceae* family is also considered a rich source of other non-peptide bioactives, particularly phenolic compounds it has been difficult to establish specific mechanistic effects (Ramadan et al., 2021). This could provide benefits by reducing the necessity to conduct purification or separation of alkaloids from phenolic compounds in the development of α-amylase and α-glucosidases inhibitory functional foods.

One common limitation of non-peptide bioactives is inconstant transfer rates though the intestinal epithelium (Xu et al., 2019). This can often limit the effectiveness of these compounds due to the inability to reach key target sights in the body. In the context of carbohydrate digestion, this is not an issue. Because α-amylase and α-glucosidase are both secreted enzymes their inhibition is not reliant on the absorption and transportation of bioactives (Ramasubbu et al., 1996).

9.3.2 Insulin Secretion and Sensitivity

As Type 2 Diabetes is a disorder associated with insulin regulation a key target for management is the augmentation of insulin metabolism (Patil et al., 2020). This can be either through the way in which the body produces and secrets insulin or by altering the natural response to the insulin that is secreted (Jahandideh et al., 2022; Seino et al., 2010).

9.3.2.1 Control of Incretin Hormone Activity

Post consumption of food insulin secretion must occur to facilitate the uptake of glucose from the bloodstream. This secretion is predominantly controlled by the incretin hormones. Out of the incretin hormones two, Glucagon-like peptide-1 (GLP-1) and Gastric inhibitory polypeptide (GIP), stimulate up to 70% of insulin secreted after the consumption of food (postprandially) (Li et al., 2018; Patil et al., 2020). Both GLP-1 and GIP are secreted by intestinal mucosal cells and bind to their respective receptors on the surface of pancreatic β-cells. This binding triggers a cascade of interactions that result in the release of insulin into the bloodstream (Seino et al., 2010). Dipeptidyl peptidase-IV (DPP-IV) is a serine protease that is responsible for the degradation of the incretin hormones. The inhibition of DPP-IV reduces the degradation of the incretin hormones, thereby maintaining pancreatic insulin secretion. As identified in Table 9.2 DPP-IV inhibition is a target of common medications used to treat and control Type 2 Diabetes.

Many of the same phenolic compounds that show effective inhibition of α-amylase and α-glucosidase have also been identified as potential DPP-IV inhibitors (Johnson et al., 2013; Les et al., 2021). Of particular concern for phenolic compounds to act as DPP-IV inhibitors is the ability to transfer through the intestinal epithelium (Xu et al., 2019). Many phenolic compounds are either insoluble or semi-soluble due to interactions with plant cell wall constituents (Shahidi & Yeo, 2016). This insolubility limits uptake by the intestinal epithelium and can be overcome by heat treatment. But, Phenolic compounds are especially susceptible to heat degradation (Mba et al., 2019). This means that the application of non-thermal methods is required to optimise the availability of phenolic compounds to act DPP-IV inhibitors. The use of non-thermal lactic acid fermentation in particular has been identified as a good approach to the liberation of phenolic compounds (Shahidi & Yeo, 2016).

Alkaloid rich extracts have been shown to act as DPP-IV inhibitors *in vivo*. Especially those derived from seeds such as fenugreek (*Trigonella foenum-graecum*), (Rasouli et al., 2020). However, more work is needed to establish specific mechanisms.

With respect to bioactive peptides, DPP-IV inhibition effects have been well established. When identifying bioactive peptides with DPP-IV inhibition activity the presence of amino acid residues with a high degree of hydrophobicity and a large number H-bond donor groups are seen as critical. This is similar to the characteristics required for peptides to have α-amylase and α-glucosidase inhibitory activity (Jakubczyk et al., 2020). However, in addition, peptides showing DPP-IV inhibition effects tend to contain, a high number of amino acid residues with aromatic ring structures (Fuentes et al., 2021). These characteristics have been identified in peptides derived from both plant and animal sources.

To function as effective DPP-IV inhibitors bioactive compounds must not only show high levels of enzymatic inhibition but also be able to survive gastrointestinal digestion and transfer across the intestinal epithelium. The use of *in silico* models has played a key role in evaluating both of these factors for bioactive peptides. Work by both Nongonierma et al. (2018) and Fuentes et al. (2021) has identified the critical role that proline can play in both providing resistance to gastrointestinal digestion and in providing DPP-IV inhibitory activity. In particular, proline in the 2nd amino acid position of tripeptides has been shown to be critical, for example, Ala-Pro-Ala, Ala-Pro-Phe, Lys-Pro-Ala, Phe-Pro-Ile, Phe-Pro-Trp, and Ile-Pro-Trp (Fuentes et al., 2021). Both red meat and dairy products are considered practically good sources of proline rich proteins (Teymoori et al., 2020). This is constant with experimental work like that of Ashraf et al. (2021) and Gallego et al. (2014).

9.3.2.2 Modulation of Insulin Receptor Expression and Sensitivity

Insulin is the key hormone regulating glucose homeostasis in the circulatory system. However, it is only able to carry out this function due to its ability to bind and interact with insulin receptors in the brain, muscle, and other organ systems (Jahandideh et al., 2022). The binding of insulin to receptors triggers a signalling cascade that simultaneously inhibits glucogenesis and enhances the uptake of glucose from the blood (Li et al., 2018). As a treatment option for Type 2 Diabetes, altering the expression or sensitivity of insulin receptors is currently underutilised. Bioactive substances derived from food have shown good potential to act in this space (Jahandideh et al., 2022; Singh et al., 2022).

The potential of non-peptide bioactives (specifically phenolic compounds and alkaloids) to act as insulin receptor modulators are understudied in comparison to other approaches to Type 2 Diabetes management (Hanhineva et al., 2010). One area of particular interest is the role that complex extracts from grains, specifically rice bran, may have in incising insulin sensitivity (Kang et al., 2019). It is believed that this interaction may be driven by the capacity of phenolic compounds to increase the expression of key genes involved in the insulin receptor pathway including Pancreatic and Duodenal Homeobox 1, Sirtuin 1, and Mitochondrial transcription factor A (Saji et al., 2020).

A number of different mechanisms have been identified for how bioactive peptides can interact with insulin receptors both in terms of the expression and in terms of the sensitivity of the receptors (Jahandideh et al., 2022). The most direct interactions that have been observed are those of peptides containing a β-hairpin motif. Peptides containing this motif have been derived from a range of plant proteins sources including pumpkin (*Cucurbita pepo*), bitter melon (*Momordica charantia*), rosemary (*Salvia rosmarinus*), grapes (*Vitis vinifera*), nuts, and seeds (Lo et al., 2016). Of particular note, is the peptide 'mcIRBP-19' originally identified and derived from the bitter melon (*Momordica charantia*). The mcIRBP-19 peptide was produced using simulated gastro intestinal digestion and showed the ability to increase glucose uptake by 2.48 fold when compared to a control (in differentiated 3T3-L1 cells) (Lo et al., 2016). Not all peptides require the β-hairpin motif to interact with insulin receptors. For example, Wang et al. (2020) identified a walnut peptide that simulated both the expression and sensitivity of insulin receptors. Finally, peptides derived from animal products have also been shown to have similar functionality. For example, Ashraf et al. (2021) demonstrated hydrolysates derived from camel's milk achieved a positive allosteric modulation of insulin receptors.

9.4 Conclusions

Bioactive compounds derived from foods (both peptide and non-peptide) have the potential to provide alternative options for the treatment of Type 2 Diabetes. Current treatments for Type 2 Diabetes are limited by the side effects they impose on patients as well as the practical ability to resolve all aspects of the illness. Bioactives derived from food have been shown to be able to act in mechanistically similar ways to current Type 2 Diabetes treatments as well as having potentially new mechanisms. Currently the extraction and purification of bioactive compounds derived from foods provides the greatest challenge to the application of these compounds. Emergent technologies are currently helping to overcome this barrier. The ability to use food waste products as a source (or in the sourcing) of bioactive compounds for the treatment of Type 2 Diabetes is also of great potential.

References

Abdelli, I., Benariba, N., Adjdir, S., Fekhikher, Z., Daoud, I., Terki, M., et al. (2021). *In Silico* evaluation of phenolic compounds as inhibitors of α-amylase and α-glucosidase. *Journal of Biomolecular Structure and Dynamics, 39*(3), 816–822.

Albuquerque, B. R., Heleno, S. A., Oliveira, M. B. P., Barros, L., & Ferreira, I. C. (2021). Phenolic compounds: Current industrial applications, limitations and future challenges. *Food & Function, 12*(1), 14–29. https://doi.org/10.1039/d0fo02324h

Anandharaj, M., Sivasankari, B., Siddharthan, N., Rani, R. P., & Sivakumar, S. (2016). Production, purification, and biochemical characterization of thermostable metallo-protease from novel *Bacillus Alkalitelluris* Twi3 isolated from Tannery waste. *Applied Biochemistry and Biotechnology, 178*(8), 1666–1686. https://doi.org/10.1007/s12010-015-1974-7

Ashraf, A., Mudgil, P., Palakkott, A., Iratni, R., Gan, C.-Y., Maqsood, S., & Ayoub, M. A. (2021). Molecular basis of the anti-diabetic properties of camel milk through profiling of its bioactive peptides on Dipeptidyl Peptidase Iv (Dpp-Iv) and insulin receptor activity. *Journal of Dairy Science, 104*(1), 61–77. https://doi.org/10.3168/jds.2020-18627

Azmir, J., Zaidul, I. S. M., Rahman, M. M., Sharif, K. M., Mohamed, A., Sahena, F., et al. (2013). Techniques for extraction of bioactive compounds from plant materials: A review. *Journal of Food Engineering, 117*(4), 426–436. https://doi.org/10.1016/j.jfoodeng.2013.01.014

Brusotti, G., Cesari, I., Dentamaro, A., Caccialanza, G., & Massolini, G. (2014). Isolation and characterization of bioactive compounds from plant resources: The role of analysis in the ethnopharmacological approach. *Journal of Pharmaceutical and Biomedical Analysis, 87*, 218–228. https://doi.org/10.1016/j.jpba.2013.03.007

Bubalo, M. C., Vidović, S., Redovniković, I. R., & Jokić, S. (2018). New perspective in extraction of plant biologically active compounds by green solvents. *Food and Bioproducts Processing, 109*, 52–73. https://doi.org/10.1016/j.fbp.2018.03.001

Caleja, C., Ribeiro, A., Filomena Barreiro, M., & CFR Ferreira, I. (2017). Phenolic compounds as nutraceuticals or functional food ingredients. *Current Pharmaceutical Design, 23*(19), 2787–2806. https://doi.org/10.2174/1381612822666161227153906

Capello, C., Wernet, G., Sutter, J., Hellweg, S., & Hungerbühler, K. (2009). A comprehensive environmental assessment of petrochemical solvent production. *The International Journal of Life Cycle Assessment, 14*(5), 467–479. https://doi.org/10.1007/s11367-009-0094-4

Caradus, J. R., Card, S. D., Finch, S. C., Hume, D. E., Johnson, L. J., Mace, W. J., & Popay, A. J. (2022). Ergot Alkaloids in New Zealand pastures and their impact. *New Zealand Journal of Agricultural Research, 65*(1), 1–41.

Casey, R., Adelfio, A., Connolly, M., Wall, A., Holyer, I., & Khaldi, N. (2021). Discovery through machine learning and preclinical validation of novel anti-diabetic peptides. *Biomedicines, 9*(3), 276. https://doi.org/10.3390/biomedicines9030276

Cerrato, A., Aita, S. E., Cavaliere, C., Laganà, A., Montone, C. M., Piovesana, S., et al. (2021). Comprehensive identification of native medium-sized and short bioactive peptides in sea bass muscle. *Food Chemistry, 343*, 128443. https://doi.org/10.1016/j.foodchem.2020.128443

Chaudhury, A., Duvoor, C., Reddy Dendi, V. S., Kraleti, S., Chada, A., Ravilla, R., et al. (2017). Clinical review of antidiabetic drugs: implications for type 2 diabetes mellitus management. *Frontiers in Endocrinology, 8*, 6. https://doi.org/10.3389/fendo.2017.00006

Dey, P., Kundu, A., Kumar, A., Gupta, M., Lee, B. M., Bhakta, T., et al. (2020). Analysis of Alkaloids (Indole Alkaloids, Isoquinoline Alkaloids, Tropane Alkaloids). In *Recent Advances in Natural Products Analysis* (pp. 505–567). Elsevier.

Dias Araujo, L., Parr, W. V., Grose, C., Hedderley, D., Masters, O., Kilmartin, P., & Valentin, D. (2021). In-mouth attributes driving perceived quality of pinot noir wines: Sensory and chemical characterisation. *Food Research International, 149*, 110665. https://doi.org/10.1016/j.foodres.2021.110665

Dima, C., Assadpour, E., Dima, S., & Jafari, S. M. (2020). Bioavailability and bioaccessibility of food bioactive compounds; overview and assessment by *in Vitro* methods. *Comprehensive Reviews in Food Science and Food Safety, 19*(6), 2862–2884. https://doi.org/10.1111/1541-4337.12623

Donovan, J. L., DeVane, C. L., Boulton, D., Dodd, S., & Markowitz, J. S. (2003). Dietary levels of quinine in tonic water do not inhibit Cyp2d6 *in Vivo*. *Food and Chemical Toxicology, 41*(8), 1199–1201.

Dusemund, B., Nowak, N., Sommerfeld, C., Lindtner, O., Schäfer, B., & Lampen, A. (2018). Risk assessment of pyrrolizidine alkaloids in food of plant and animal origin. *Food and Chemical Toxicology, 115*, 63–72. https://doi.org/10.1016/j.fct.2018.03.005

Ellwood, K., Balentine, D. A., Dwyer, J. T., Erdman, J. W., Jr., Gaine, P. C., & Kwik-Uribe, C. L. (2014). Considerations on an approach for establishing a framework for bioactive food components. *Advances in Nutrition, 5*(6), 693–701. https://doi.org/10.3945/an.114.006312

Espósito, T. S., Amaral, I. P., Buarque, D. S., Oliveira, G. B., Carvalho, L. B., Jr., & Bezerra, R. S. (2009). Fish processing waste as a source of alkaline proteases for laundry detergent. *Food Chemistry, 112*(1), 125–130. https://doi.org/10.1016/j.foodchem.2008.05.049

Fernández-García, E., Carvajal-Lérida, I., & Pérez-Gálvez, A. (2009). *In Vitro* Bioaccessibility assessment as a prediction tool of nutritional efficiency. *Nutrition Research, 29*(11), 751–760. https://doi.org/10.1016/j.nutres.2009.09.016

Fuentes, L. R., Richard, C., & Chen, L. (2021). Sequential Alcalase and Flavourzyme treatment for preparation of α-amylase, α-glucosidase, and Dipeptidyl Peptidase (Dpp)-Iv inhibitory peptides from oat protein. *Journal of Functional Foods, 87*, 104829.

Fuster, V., & Sweeny, J. M. (2011). Aspirin: A historical and contemporary therapeutic overview. *Circulation, 123*(7), 768–778. https://doi.org/10.1161/CIRCULATIONAHA.110.963843

Gaikwad, S. B., Krishna Mohan, G., & Sandhya Rani, M. (2014). Phytochemicals for diabetes management. *Pharmaceutical Crops, 5*, 11–28. https://doi.org/10.2174/2210290601405010011

Gallego, M., Aristoy, M.-C., & Toldrá, F. (2014). Dipeptidyl Peptidase Iv inhibitory peptides generated in spanish Dry-Cured Ham. *Meat Science, 96*(2), 757–761. https://doi.org/10.1016/j.meatsci.2013.09.014

Giacometti, J., Bursać Kovačević, D., Putnik, P., Gabrić, D., Bilušić, T., Krešić, G., et al. (2018). Extraction of bioactive compounds and essential oils from mediterranean herbs by conventional and green innovative techniques: A review. *Food Research International, 113*, 245–262. https://doi.org/10.1016/j.foodres.2018.06.036

González-Montoya, M., Hernández-Ledesma, B., Mora-Escobedo, R., & Martínez-Villaluenga, C. (2018). Bioactive peptides from germinated Soybean with anti-diabetic potential by inhibition of Dipeptidyl Peptidase-Iv, α-amylase, and α-glucosidase enzymes. *International Journal of Molecular Sciences, 19*(10), 2883.

Görgüç, A., Gençdağ, E., & Yılmaz, F. M. (2020). Bioactive peptides derived from plant origin by-products: Biological activities and techno-functional utilizations in food developments – A review. *Food Research International, 136*, 109504. https://doi.org/10.1016/j.foodres.2020.109504

Gullón, P., Gullón, B., Romaní, A., Rocchetti, G., & Lorenzo, J. M. (2020). Smart advanced solvents for bioactive compounds recovery from agri-food by-products: A review. *Trends in Food Science & Technology, 101*, 182–197. https://doi.org/10.1016/j.tifs.2020.05.007

Ha, M., Bekhit, A. E.-D. A., Carne, A., & Hopkins, D. L. (2012). Characterisation of commercial Papain, Bromelain, Actinidin and Zingibain Protease preparations and their activities toward meat proteins. *Food Chemistry, 134*(1), 95–105.

Haminiuk, C. W., Maciel, G. M., Plata-Oviedo, M. S., & Peralta, R. M. (2012). Phenolic compounds in fruits–An overview. *International Journal of Food Science & Technology, 47*(10), 2023–2044.

Hanhineva, K., Törrönen, R., Bondia-Pons, I., Pekkinen, J., Kolehmainen, M., Mykkänen, H., & Poutanen, K. (2010). Impact of dietary polyphenols on carbohydrate metabolism. *International Journal of Molecular Sciences, 11*(4), 1365–1402.

Harnly, J. (2017). Antioxidant methods. *Journal of Food Composition and Analysis, 64*, 145–146. https://doi.org/10.1016/j.jfca.2017.08.011

Hellinger, R., & Gruber, C. W. (2019). Peptide-based protease inhibitors from plants. *Drug Discovery Today, 24*(9), 1877–1889. https://doi.org/10.1016/j.drudis.2019.05.026

Ingle, K. P., Deshmukh, A. G., Padole, D. A., Dudhare, M. S., Moharil, M. P., & Khelurkar, V. C. (2017). Phytochemicals: Extraction methods, identification and detection of bioactive compounds from plant extracts. *Journal of Pharmacognosy and Phytochemistry, 6*(1), 32–36.

Jahandideh, F., Bourque, S. L., & Wu, J. (2022). A comprehensive review on the glucoregulatory properties of food-derived bioactive peptides. *Food Chemistry, X*, 100222.

Jakubczyk, A., Karaś, M., Rybczyńska-Tkaczyk, K., Zielińska, E., & Zieliński, D. (2020). Current trends of bioactive peptides—New sources and therapeutic effect. *Foods, 9*(7), 846.

Jan, F., Kumar, S., & Jha, R. (2016). Effect of boiling on the antidiabetic property of enzyme treated sheep milk casein. *Veterinary World, 9*(10), 1152. https://doi.org/10.14202/vetworld.2016.1152-1156

Ji, Y., Liu, D., Jin, Y., Zhao, J., Zhao, J., Li, H., et al. (2021). *In Vitro* and *in Vivo* inhibitory effect of Anthocyanin-Rich Bilberry extract on α-glucosidase and α-amylase. *LWT, 145*, 111484. https://doi.org/10.1016/j.lwt.2021.111484

Johnson, M. H., De Mejia, E. G., Fan, J., Lila, M. A., & Yousef, G. G. (2013). Anthocyanins and proanthocyanidins from blueberry–Blackberry fermented beverages inhibit markers of inflammation in macrophages and carbohydrate-utilizing enzymes *in Vitro*. *Molecular Nutrition & Food Research, 57*(7), 1182–1197.

Kang, G. G., Francis, N., Hill, R., Waters, D., Blanchard, C., & Santhakumar, A. B. (2019). Dietary polyphenols and gene expression in molecular pathways associated with type 2 diabetes mellitus: A review. *International Journal of Molecular Sciences, 21*(1), 140.

Karami, Z., & Akbari-Adergani, B. (2019). Bioactive food derived peptides: A review on correlation between structure of bioactive peptides and their functional properties. *Journal of Food Science and Technology, 56*(2), 535–547. https://doi.org/10.1007/s13197-018-3549-4

Kay, S.-I. S., Delgado, S., Mittal, J., Eshraghi, R. S., Mittal, R., & Eshraghi, A. A. (2021). Beneficial effects of milk having A2 B-Casein protein: Myth or reality? *The Journal of nutrition, 151*(5), 1061–1072. https://doi.org/10.1093/jn/nxaa454

Klotz, J. L. (2022). Global impact of ergot alkaloids. *Toxins, 14*(3), 186. https://doi.org/10.3390/toxins14030186

Korhonen, H., & Pihlanto, A. (2006). Bioactive peptides: Production and functionality. *International Dairy Journal, 16*(9), 945–960. https://doi.org/10.1016/j.idairyj.2005.10.012

Laraia, L., Robke, L., & Waldmann, H. (2018). Bioactive compound collections: From design to target identification. *Chem, 4*(4), 705–730. https://doi.org/10.1016/j.chempr.2018.01.012

Les, F., Cásedas, G., Gómez, C., Moliner, C., Valero, M. S., & López, V. (2021). The role of anthocyanins as antidiabetic agents: From molecular mechanisms to in vivo and human studies. *Journal of Physiology and Biochemistry, 77*(1), 109–131.

Li, S., Liu, L., He, G., & Wu, J. (2018). Molecular targets and mechanisms of bioactive peptides against metabolic syndromes. *Food & Function, 9*(1), 42–52. https://doi.org/10.1039/c7fo01323j

Lo, H.-Y., Li, C.-C., Ho, T.-Y., & Hsiang, C.-Y. (2016). Identification of the bioactive and consensus peptide motif from momordica charantia insulin receptor-binding protein. *Food Chemistry, 204*, 298–305. https://doi.org/10.1016/j.foodchem.2016.02.135

Mahato, N., Sinha, M., Sharma, K., Koteswararao, R., & Cho, M. H. (2019). Modern extraction and purification techniques for obtaining high purity food-grade bioactive compounds and value-added co-products from citrus wastes. *Foods, 8*(11), 523. https://doi.org/10.3390/foods8110523

Maldonado, C., Barnes, C. J., Cornett, C., Holmfred, E., Hansen, S. H., Persson, C., et al. (2017). Phylogeny predicts the quantity of antimalarial alkaloids within the iconic yellow Cinchona Bark (*Rubiaceae: Cinchona Calisaya*). *Frontiers in Plant Science, 8*, 391. https://doi.org/10.3389/fpls.2017.00391

Matsuura, H. N., & Fett-Neto, A. G. (2015). Plant alkaloids: Main features, toxicity, and mechanisms of action. *Plant Toxins, 2*(7), 1–15.

Mba, O. I., Kwofie, E. M., & Ngadi, M. (2019). Kinetic modelling of polyphenol degradation during common beans soaking and cooking. *Heliyon, 5*(5), e01613. https://doi.org/10.1016/j.heliyon.2019.e01613

Minervini, F., Algaron, F., Rizzello, C. G., Fox, P. F., Monnet, V., & Gobbetti, M. (2003). *Applied and Environmental Microbiology, 69*(9), 5297–5305. https://doi.org/10.1128/AEM.69.9.5297-5305.2003

Misra, H., Mehta, B. K., & Jain, D. C. (2008). Optimization of extraction conditions and Hptlc-Uv method for determination of quinine in different extracts of cinchona species bark. *Records of Natural Products, 2*(4), 107–115.

Montinari, M. R., Minelli, S., & De Caterina, R. (2019). The first 3500 years of aspirin history from its roots–A concise summary. *Vascular Pharmacology, 113*, 1–8.

National Center for Biotechnology Information. (2022). *Pubchem Compound Summaries*. Retrieved February 9, 2022 from https://pubchem.ncbi.nlm.nih.gov/

Nongonierma, A. B., Dellafiora, L., Paolella, S., Galaverna, G., Cozzini, P., & FitzGerald, R. J. (2018). *In Silico* approaches applied to the study of peptide analogs of Ile-Pro-Ile in relation to their dipeptidyl peptidase Iv inhibitory properties. *Frontiers in Endocrinology, 9*, 329. https://doi.org/10.3389/fendo.2018.00329

Patil, S. P., Goswami, A., Kalia, K., & Kate, A. S. (2020). Plant-derived bioactive peptides: A treatment to cure diabetes. *International Journal of Peptide Research and Therapeutics, 26*(2), 955–968. https://doi.org/10.1007/s10989-019-09899-z

Ramadan, S., Hegab, A. M., Al-Awthan, Y. S., Al-Duais, M. A., Tayel, A. A., & Al-Saman, M. A. (2021). Comparison of the efficiency of *Lepidium Sativum, Ficus Carica, and Punica Granatum* methanolic extracts in relieving hyperglycemia and hyperlipidemia of streptozotocin-induced diabetic rats. *Journal of Diabetes Research, 2021*, 6018835. https://doi.org/10.1155/2021/6018835

Ramakodi, M. P., Santhosh, N., Pragadeesh, T., Mohan, S. V., & Basha, S. (2020). Production of protease enzyme from slaughterhouse effluent: An approach to generate value-added products from waste. *Bioresource Technology Reports, 12*, 100552.

Ramasubbu, N., Paloth, V., Luo, Y., Brayer, G. D., & Levine, M. J. (1996). Structure of human salivary α-amylase at 1.6 Å resolution: Implications for its role in the oral cavity. *Acta Crystallographica Section D: Biological Crystallography, 52*(3), 435–446.

Rasouli, H., Yarani, R., Pociot, F., & Popović-Djordjević, J. (2020). Anti-diabetic potential of plant alkaloids: Revisiting current findings and future perspectives. *Pharmacological Research, 155*, 104723. https://doi.org/10.1016/j.phrs.2020.104723

Recharla, N., Riaz, M., Ko, S., & Park, S. (2017). Novel technologies to enhance solubility of food-derived bioactive compounds: A review. *Journal of Functional Foods, 39*, 63–73. https://doi.org/10.1016/j.jff.2017.10.001

Reyes, C. M., & Cornelis, M. C. (2018). Caffeine in the diet: Country-level consumption and guidelines. *Nutrients, 10*(11), 1772. https://doi.org/10.3390/nu10111772

Rezaei, M., Valiee, S., Tahan, M., Ebtekar, F., & Ghanei Gheshlagh, R. (2019). Barriers of medication adherence in patients with type-2 diabetes: A pilot qualitative study. *Diabetes, Metabolic Syndrome and Obesity: Targets and Therapy, 12*, 589–599. https://doi.org/10.2147/DMSO.S197159

Ryan, C. A. (1990). Protease inhibitors in plants: Genes for improving defenses against insects and pathogens. *Annual Review of Phytopathology, 28*(1), 425–449. https://doi.org/10.1146/annurev.py.28.090190.002233

Ryder, K., Bekhit, A. E.-D., McConnell, M., & Carne, A. (2016). Towards generation of bioactive peptides from meat industry waste proteins: Generation of peptides using commercial microbial proteases. *Food Chemistry, 208*, 42–50. https://doi.org/10.1016/j.foodchem.2016.03.121

Sagar, N. A., Pareek, S., Sharma, S., Yahia, E. M., & Lobo, M. G. (2018). Fruit and vegetable waste: Bioactive compounds, their extraction, and possible utilization. *Comprehensive Reviews in Food Science and Food Safety, 17*(3), 512–531. https://doi.org/10.1111/1541-4337.12330

Saji, N., Francis, N., Schwarz, L. J., Blanchard, C. L., & Santhakumar, A. B. (2020). Rice bran phenolic extracts modulate insulin secretion and gene expression associated with B-cell function. *Nutrients, 12*(6), 1889.

Samtiya, M., Aluko, R. E., & Dhewa, T. (2020). Plant food anti-nutritional factors and their reduction strategies: An overview. *Food Production, Processing and Nutrition, 2*(1), 1–14.

Sánchez-Rivera, L., Martínez-Maqueda, D., Cruz-Huerta, E., Miralles, B., & Recio, I. (2014). Peptidomics for discovery, bioavailability and monitoring of dairy bioactive peptides. *Food Research International, 63*, 170–181. https://doi.org/10.1016/j.foodres.2014.01.069

Sarmadi, B. H., & Ismail, A. (2010). Antioxidative peptides from food proteins: A review. *Peptides, 31*(10), 1949–1956. https://doi.org/10.1016/j.peptides.2010.06.020

Seino, Y., Fukushima, M., & Yabe, D. (2010). Gip and Glp-1, the two incretin hormones: Similarities and differences. *Journal of Diabetes Investigation, 1*(1-2), 8–23. https://doi.org/10.1111/j.2040-1124.2010.00022.x

Shahidi, F., & Yeo, J. (2016). Insoluble-bound phenolics in food. *Molecules, 21*(9), 1216. https://doi.org/10.3390/molecules21091216

Singh, S., Bansal, A., Singh, V., Chopra, T., & Poddar, J. (2022). Flavonoids, alkaloids and terpenoids: A new hope for the treatment of diabetes mellitus. *Journal of Diabetes & Metabolic Disorders, 21*, 1–10.

Somashekhar, M., Nayeem, N., & Sonnad, B. (2013). A review on family *Moraceae* (Mulberry) with a focus on artocarpus species. *World Journal of Pharmacy and Pharmaceutical Sciences, 2*(5), 2614–2626.

Tabart, J., Kevers, C., Pincemail, J., Defraigne, J.-O., & Dommes, J. (2009). Comparative antioxidant capacities of phenolic compounds measured by various tests. *Food Chemistry, 113*(4), 1226–1233. https://doi.org/10.1016/j.foodchem.2008.08.013

Teymoori, F., Asghari, G., Farhadnejad, H., Nazarzadeh, M., Atifeh, M., Mirmiran, P., & Azizi, F. (2020). Various proline food sources and blood pressure: Substitution analysis. *International Journal of Food Sciences and Nutrition, 71*(3), 332–340.

Toldrá, F., Reig, M., Aristoy, M.-C., & Mora, L. (2018). Generation of bioactive peptides during food processing. *Food Chemistry, 267*, 395–404. https://doi.org/10.1016/j.foodchem.2017.06.119

Tuomi, T., Santoro, N., Caprio, S., Cai, M., Weng, J., & Groop, L. (2014). The many faces of diabetes: A disease with increasing heterogeneity. *The Lancet, 383*(9922), 1084–1094. https://doi.org/10.1016/S0140-6736(13)62219-9

Udenigwe, C. C. (2014). Bioinformatics approaches, prospects and challenges of food bioactive peptide research. *Trends in Food Science & Technology, 36*(2), 137–143. https://doi.org/10.1016/j.tifs.2014.02.004

Unuofin, J. O., & Lebelo, S. L. (2020). Antioxidant effects and mechanisms of medicinal plants and their bioactive compounds for the prevention and treatment of type 2 diabetes: An updated review. *Oxidative Medicine and Cellular Longevity, 2020*, 1356893. https://doi.org/10.1155/2020/1356893

van Dieren, S., Beulens, J. W. J., van der Schouw, Y. T., Grobbee, D. E., & Nealb, B. (2010). The global burden of diabetes and its complications: An emerging pandemic. *European Journal of Cardiovascular Prevention & Rehabilitation, 17*(1_suppl), s3–s8. https://doi.org/10.1097/01.hjr.0000368191.86614.5a

Wang, J., Wu, T., Fang, L., Liu, C., Liu, X., Li, H., et al. (2020). Anti-diabetic effect by walnut (*Juglans Mandshurica Maxim.*)-Derived Peptide Lpllr through inhibiting α-glucosidase and α-amylase, and alleviating insulin resistance of hepatic Hepg2 Cells. *Journal of Functional Foods, 69*, 103944.

Xu, Q., Hong, H., Wu, J., & Yan, X. (2019). Bioavailability of bioactive peptides derived from food proteins across the intestinal epithelial membrane: A review. *Trends in Food Science & Technology, 86*, 399–411. https://doi.org/10.1016/j.tifs.2019.02.050

Yan, J., Zhao, J., Yang, R., & Zhao, W. (2019). Bioactive peptides with antidiabetic properties: A review. *International Journal of Food Science & Technology, 54*(6), 1909–1919. https://doi.org/10.1111/ijfs.14090

Yin, Z., Zhang, W., Feng, F., Zhang, Y., & Kang, W. (2014). α-glucosidase inhibitors isolated from medicinal plants. *Food Science and Human Wellness, 3*(3), 136–174. https://doi.org/10.1016/j.fshw.2014.11.003

Yu, Z., Yin, Y., Zhao, W., Liu, J., & Chen, F. (2012). Anti-diabetic activity peptides from albumin against α-glucosidase and α-amylase. *Food Chemistry, 135*(3), 2078–2085. https://doi.org/10.1016/j.foodchem.2012.06.088

Zainal-Abidin, M. H., Hayyan, M., Hayyan, A., & Jayakumar, N. S. (2017). New horizons in the extraction of bioactive compounds using deep eutectic solvents: A review. *Analytica Chimica Acta, 979*, 1–23. https://doi.org/10.1016/j.aca.2017.05.012

10 Understanding New Foods: Alternative Protein Sources

Jeff Caminiti, Aishwarya Badiger, Omega Amoafo, and Luca Serventi

Abstract

This chapter discusses alternative protein sources and their potential to make novel and sustainable foods. A constantly increasing human population, global warming, and reduced availability of arable land for agriculture has been the cause of concerns for scientists and governments in recent years. The exploration of food and protein sources that require less land and water while emitting fewer greenhouse gasses during cultivation is important for future development. Algae, insects, fungi, and other fermented food sources were identified and discussed for their sustainable production potential. Algae, including seaweed and microalgae, are photosynthetic organisms with a high diversity of nutritional benefits. Seaweeds have additional benefits of bioremediation when grown in the open ocean. Insects are high in protein and require less land and water needed to produce staple crops such as soy. Algae and insects' main challenges are consumer acceptance requiring transformation into familiar forms for a better appeal. Fungi can produce fibers that allow for meat mimicry increasing consumer acceptance. Fermentation technologies, including microalgae, single-celled protein, and lab-grown meat promise sustainable production of highly specific and functional proteins for use in meat mimicry or other products. Agriculture is a fundamental aspect of life that is also responsible for a considerable amount of emissions and damage to global ecosystems. Developments of novel technologies and foods are needed to combat these issues. More work is needed to develop palatable foods from algae, insects, and fungi. These alternative protein sources are one answer to more sustainable systems that reduce emissions and increase overall resilience.

Keywords

Algae · Insects · Fungi · Alternative protein · Sustainability

10.1 Introduction

Advances in farming techniques reduce the time and effort needed to acquire food, allowing our species to grow and spread across the world. With the population set to reach 11 billion by the

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end of the century, scientists and governments have voiced concerns over global food security (Hasegawa et al., 2018; UN, 2019). Challenges associated with global warming exacerbate food insecurity by altering climates in once bountiful regions, changing ocean ecosystems, and generally increasing global temperatures, among many other challenges, reviewed by (Bezner Kerr et al., 2022; Neupane et al., 2022). Western cultures are heavily reliant on animal agriculture which is associated with the degradation of the environment through deforestation and excessive water and land use along with high emissions (Goldstein et al., 2017). While modern agriculture technology will be essential in combating global food insecurity, some of the current practices exacerbate climate change and damage ecosystems.

Globally, agriculture is a major contributor to greenhouse gas emissions (GHGE). Governmental reports have calculated that agriculture is responsible for approximately 20% of anthropogenic emissions (FAO, 2020). An academic study even suggests the food system is responsible for 34% of emissions with 71% coming from the effects of high land usage (Crippa et al., 2021). Furthermore, the crops that are grown on these vast expanses of land are often monocultures which severely affected soil biodiversity leading to concerns about long-term crop stability and potentially famine (Thrupp, 2000; Wang et al., 2019). The need for foods with low land requirements was used to select the alternative food sources discussed in this chapter. The food sources discussed below are also expected to either increase or not affect the biodiversity of the natural environment by moving cultivation off the large areas of land. As we improve food production techniques for the future, the goal is to do so in a manner that allows ecosystems to revive themselves. Novel sources of food and processing technologies can and are being used to ensure the global population is fed, but do so while conserving biodiversity, and reducing climate impacts.

It should not come to a surprise that, in the recent years, consumers have increasingly sought alternative sources of protein. Terms such "flexitarian", "vegan" and "plant based" have appeared on food labels. Flexitarians and plant-based consumers are those who reduce their meat intake, while vegans abstain entirely from any kind of animal derived food (Dagevos, 2021). Consumers' main drivers were ethics, health and environment (Aschemann-Witzel et al., 2021; Dagevos, 2021; Estell et al., 2021; Michel et al., 2021). Online surveys carried in Australia and Germany depicted as high as 20% flexitarian, 2/3 of which being women (Estell et al., 2021; Michel et al., 2021). This nutritional shift is a growing phenomenon in western countries of America, Europe and Oceania, whereas it does not appear to be popular in Africa and Asia. This was possibly associated to the socio-economic status of emerging economies which typically is associated to increase meat intake (Dagevos, 2021). What does it entail? Soy, pea, wheat isolates, but also microalgae, insects, mycroprotein and cultured meat (Onwezen et al., 2021). Consumers' main drivers were ethics, health and environment. Convenience and taste are not optimal yet, (Aschemann-Witzel et al., 2021). In addition, some products sold as alternative proteins tend to be highly processed and perceived as less natural by consumers (Varela et al., 2022). Thus, improvements are needed for such products.

Veggie-burgers have had a niche role in the American food system for the last half century, but recently Impossible Foods™ hit mainstream headlines when it began producing a plant-based burger that bleeds. The founder, Pat Brown, set out to make a better veggie burger and "save the planet" from the massive emissions associated with factory farming during a sabbatical from Stanford in 2009. For many consumers the Impossible is their first experience with "veggie burgers," while the company is leading an emerging billion-dollar industry of plant-based burgers and other alternative meat products. The major companies in this emerging U.S. alternative protein industry are Impossible Foods and Beyond Meat, both of whom were founded for the sole purpose of displacing future growth of the meat industry. Increasingly, food technology companies are making use of combinations of protein sources and novel ingredients, which in the past have either been consumed separately or hadn't existed until a few years back. There is an interplay of different processes in the alternative protein space to generate the desired final product convincing enough for consumers as meat replacements. For example, the Impossible burger uses soy protein as its primary ingredient which has been used as a key ingredient in many cultures for centuries, however, their product is set apart by the inclusion of "heme" derived from a highly scaled precision fermentation process (Impossiblefoods.com, accessed May 2022).

In this chapter, we discuss novel sources of foods and emerging food ingredients which may be implemented in sustainable food systems of the future. This chapter hopes to move past the regional novelty of certain food sources and focus on novelties that were created or promoted for a singular purpose – sustainability. With many environmentally favorable novel food-based ingredients, such as insect, microalgae, seaweed, or fungus, commercial products are still under development so the food source will be the major focus.

10.2 Algae

Algae is a collective term for photosynthetic Eukaryotic organisms not classified as plants, most of which do not share a common ancestor. While prokaryotic, certain cyanobacteria, such as *Spirulina,* are referred to as blue-green algae and are typically included in discussions of algae (Torres-Tiji et al., 2020). This diverse group of organisms are divided into two broad groups based primarily on size including the microscopic (microalgae) and the macroscopic (macroalgae). Algae should be considered a promising food of the future, but maybe not a novel source as they have been a source of nutrients to humans for much of our history with the oldest known records have identified its use 14,00 years ago (Torres-Tiji et al., 2020). The diversity in the biology of these organisms provides both promise and challenge for the development of novel food products. While attempts to use algae as a source of nutrients for a growing world population were attempted in the last century, technological advancements and shifts in consumer priorities have increased interest from investors in recent years. Broadly speaking, algae has been championed as food of the future, a nutrient source to meet the needs of our growing population, for their: low land use, and sustainable production (Baghel et al., 2015), diverse functionality, and robust nutritional properties (Wells et al., 2017).

Macroalgae have been a consistent staple of global cuisines. A great deal of seaweed's rich history has been published previously (Kaori & Connor, 2017). The most recognizable seaweed-derived food item is Nori, a product made from *Porphyra* and widely used in sushi. Nori, Wakame (*Undaria pinnatifida),* Kombu (*Laminaria japonica*), Dulse (*Palmaria palmata* or *Rhodymenia sp*) are three of the most commercially successful varieties of seaweed (Griffiths et al., 2016). Microalgae have followed a different path as governments in the 1940's and '50s viewed microalgae, specifically *Chlorella pyrenoidosa,* as a high-tech solution to the rising population and hunger in the world (Belasco, 1997). Much of these same hopes are shared within the food industry today with the added motivation of developing sustainable crops to feed the world in the face of climate change and for ecological repair. While research and development in transforming microalgae into food were significant after WWII, it is obvious to many readers that these efforts did not produce the desired outcome. Both technical and economic factors led to microalgae being a poor vehicle to combat hunger but instead, a few select varieties become moderately popular health supplements (Belasco, 1997). *Arhrospira*, commercially known as *Spirulina*, was reintroduced into western minds after a Belgian botanist observed it in African markets (Matufi & Choopani, 2020), which reignited interest in microalgae's superior physical and nutritional properties in the late 1960's (Belasco, 1997). Unfortunately, these, and other, single-celled proteins were not able to deliver as cheap protein sources through the latter part of the twentieth century but instead found niche markets for health conscience consumers able to pay a premium (Belasco, 1997; Matufi & Choopani, 2020).

Though their utilization is low compared to many traditional crops, micro- and macroalgae provide diverse solutions to enhance the sustainability of the food system. To better understand this potential, a brief description of their cultivation is helpful. First, all algae photosynthesize making them primary sources of nutrients and providing a carbon sink as they use atmospheric CO_2 to create energy. This does not mean algae foods will be carbon negative, but it helps reduce their final carbon footprint after processing, storage, transportation, and other necessary steps in food production. Microalgae are rarely collected from the wild for commercial purposes. Instead, a single strain is identified and cultivated in large ponds or raceways with controlled substrates, agitation, and other parameters to maximize growth (Suparmaniam et al., 2019). While control and yield are maximized if this process is conducted indoors with advanced light management systems, being able to forgo artificial light and the associated energy costs often make outdoor cultivation the preferred method from a sustainability perspective. However, with the rise of renewable energy, increased process controls, and more flexibility in the site of the farm, indoor cultivation remains a viable option. The cultivation of microalgae is another example of fermentation technology. Microalgae have also been the subject of selective breeding and genetic modification to enhance specific traits such as growth rate or a particular biomolecule (Torres-Tiji et al., 2020). The high levels of control and ease genetic manipulations make microalgae an exciting source of novel and sustainable proteins.

Certain seaweeds are also grown indoors, but this is a much smaller portion compared to microalgae. The benefits of seaweed cultivation are wide-ranging. Like microalgae, seaweed is a primary source of nutrients in that it photosynthesizes to sequester atmospheric carbon and create new material. Macroalgae's sustainability attributes are wide-ranging aside from the carbon sequestration, land, and water footprints (Baghel et al., 2015). Macroalgae are typically farmed in the ocean; when placed strategically, they sequester excess nitrogen from the water benefiting the ecosystem, if harvested (Murphy et al., 2015). A small-scale push to create 3-D farms that include a variety of sea crops is expected to increase fish populations and biodiversity while providing a stable year-round harvest (Bren Smith, 2019). The specifics of the impact will depend on many factors and need to be studied for unintended impacts. If grown in polluted waters bioaccumulation may be problematic so producers should always maintain quality control for clean and potentially hazardous harvests of algae.

A biorefinery approach for maximizing utilization is an important way to enhance sustainability by maximizing the utility of all algal components regardless of quality. This process aims to mimic oil refinery in producing multiple saleable goods, but, in the case of biorefinery, food and feed are often potential products that can help valorize the original biomass if food safety is maintained (Chew et al., 2017). This process has been studied extensively and may be the ideal choice when creating extracts or isolates from both micro- and macroalgae biomass (Baghel et al., 2015; Greene et al., 2020; Subhadra & Grinson-George, 2011).

Whole seaweeds contain unique and diverse flavors and textures when eaten whole, but their extracts and microalgae are most likely to be consumed as an ingredient in a more complex food product. The local seaweed and the regional cuisines of whole macroalgae have been discussed thoroughly in association with the Chinese (Xia & Abbott, 1987) and Alaskan (Garza & Program, 2005) regions. Due to logistics and consumer perception, whole algae is expected to have only a limited impact. Whole microalgae powders are sold as supplements and are often mixed into food or drink (Griffiths et al., 2016). Powders along with various extracts of either type of algae are sold as emulsifiers, thickeners, gelling agents, and colorants (Gouveia et al., 2008). In efforts to curtail the use of unstainable animal-based agricultural products, algae have been studied as an ingredient in meat mimetic products (Grahl et al., 2018). Perhaps the most important aspect of algal sustainability is its ability to provide sufficient protein to displace the need for future animal agriculture investment. The topic of replacing meat with algae has been studied along with other alternative proteins and it was found that nutrition or wellness benefits associated with algae were a highly influential factor in increasing the novel, algae-containing, products' willingness-to-eat in consumers (Onwezen et al., 2021).

The nutritional profiles are possibly the most compelling reason for the continued adoption of algae foods. The best word to describe algal nutrition is diversity. As with any large class of organism, the specific nutritional benefits of one variety are not guaranteed to be present in others. This natural diversity is amplified in the algae due to the loose qualifications for what makes an organism an alga. Furthermore, the way macroalgae grow naturally, freely in an open body of water, makes them susceptible to changes in the composition, temperature, and light available in that water (Renaud & Luong-Van, 2006). Diversity in nutrition does pose a challenge to food processors, but it should also be celebrated as an opportunity to develop diets capable of providing complete and wholesome nutrition for the globe.

Only a small fraction of the micro- and macroalgae have been used in food and within that, a smaller fraction has been approved by a governmental agency for sale as food (Barros de Medeiros et al., 2021). More than 6,500 species of macroalgae are known worldwide categorized into three groups: brown (Phaeophyta; 1,500), red (Rhodophyta; 4,000), or green (Chlorophyta; 1,000) (Garza & Program, 2005). Brown seaweed often referred to as kelp, is typically the largest of the seaweeds. High carbohydrate contents containing alginates and fucoidans are often characteristics of kelp. While low in protein, these seaweeds are the group most commonly used by the food industry due to the diverse and useful properties of their carbohydrates (Afonso et al., 2019). Red seaweed is commonly used in the production of agar and carrageenan as stabilizers, emulsifiers, and homogenizers. They are typically lower in fat but contain a diverse array of micronutrients and pigments while being as high as 47% protein making them a desirable source of novel protein (Cotas et al., 2020). Green seaweed has been called "Green Caviar" for its "delicate flavor and crisp texture" and like other seaweeds is packed with macro- and micronutrients (Magdugo et al., 2020). The fatty acid, amino acid, and mineral profiles of a given seaweed will vary depending on the phyla and species as well as on harvest location and season (Renaud & Luong-Van, 2006). Seaweeds have great potential to enhance human nutrition around the world while providing unique physical and bioactive functionality for broad incorporation into many diets and cuisines.

The number of microalgae species on the planet is not known and due to the nature of microorganisms, is constantly changing. However, with our current understanding, the number of microalgal species dwarfs that of macroalgae by orders of magnitude with estimates coming in from 200,000 to over a million (Koyande et al., 2019; Matos, 2019). Nonetheless, the diversity issues discussed with macroalgae are not as prevalent in microalgae food production, primarily due to higher levels of cultivation control. In microalgae production, the challenges come with isolating and mass-cultivating a GRAS (generally recognized as safe) strain with a sufficiently high growth rate. Only a few microalgae have been granted GRAS status by the US FDA *Arthrospira platensis, Chlamydomonas reinhardtii, Auxenochlorella protothecoides, Chlorellavulgaris, Dunaliella bardawil, and Euglena gracilis;* while many other species are likely safe to eat obtaining GRAS status can be costly. (Torres-Tiji et al., 2020) provides an in-depth review of these microalgae which is beyond the scope of this chapter. *Spirulina, and Chlorella* are the most used microalgae in human nutrition, animal nutrition, and cosmetics (Barros de Medeiros et al., 2021; Torres-Tiji et al., 2020). *Dunaliella* is the next most cultivated for human nutrition and is of great interest for its beta-carotene content (Koyande et al., 2019; Torres-Tiji et al., 2020). The remaining GRAS strains are produced at lower quantifies for human nutrition products and oil production (Torres-Tiji et al., 2020). In general microalgae are higher in protein than their macroalgal cousins and often express favorable amino acid profiles (Matos, 2019; Wang et al., 2021). As a human food and as a biofuel feedstock the lipid fraction of microalgae is highly sought after (Talebi et al., 2013). While microalgae are often higher in "good fats," those high in polyunsaturated fatty acids (PUFA's), it is difficult to predict their fatty acid profile as they are dependent on environment and species (Lang et al., 2011; Teoh et al., 2004). Microalgae provide B vitamins, an essential nutrient; often deficient in vegan diets (Koyande et al., 2019). A great deal of algae research, outside what is cited in this chapter, has been conducted on a multitude of different species, strains and with differing conditions. This research shows that microalgae can be a reliable source of nutrients to meet the rapidly changing demands of our global food system.

10.3 Fermentation-Based Ingredients

In the context of the alternative protein industry, fermentation-based innovations can be categorized into traditional fermentation, biomass fermentation and precision fermentation. Traditional fermentation has been done for centuries and can be commonly seen in products such as bread or beer to modify functional properties of the product such as flavor, nutrition, and physical structure. Biomass fermentation uses the ability of micro-organisms to rapidly multiply and break down substrates to generate high protein end products efficiently. Precision fermentation uses microorganisms to produce certain key ingredients that can improve the sensory properties of alternative protein products.

10.3.1 Mycoprotein

One of the reasons the mycoprotein industry started growing rapidly was the fact that most edible fungi exhibit complete amino acid profiles, grow rapidly, and are able to use waste biomass as a substrate, thus vastly reducing costs associated with production. Fungi are natural decomposers due to their ability to break down complex biomass mainly through the production of enzymes. This can also be categorized under the upcycling (adding value to food waste) industry which according to ReFED's (Rethink Food Waste through Economics and Date) Insights Engine has an estimated impact of 4.85 M Metric Tons of carbon dioxide emissions per year. Coupled with the scalability of fermentation technologies, mycoprotein has been disrupting the market ever since the discovery and regulatory approval of the Quorn™ fungus.

Although the consumption of edible fungi dates back centuries, it wasn't until the late twentieth century that their full potential was explored due to developments in industrial microbiology (Wiebe, 2002). *Fusarium venenatum* or the Quorn™ fungus was first studied as a mycoprotein source in the 1960s. It took 12 years of safety testing to ensure it wasn't a potential plant pathogen or mycotoxin producing before it was approved for use as a food in 1984. For a long time, this was the primary source of mushroom protein with regulatory approval on the market. In fact, a lot of literature on fungi protein uses the term mycoprotein interchangeably with protein derived from *Fusarium venenatum*. However, in this chapter, mycoprotein is considered as a broader class encompassing protein derived from any edible fungi.

There have been considerable advances and newer innovations in the mycoprotein space. In addition to a mass of research (Ahmad et al., 2022) investigating newer strains, nutritional characteristics, more efficient forms of fermentation, the mycoprotein space has seen a few commercial successes as well. *Fusarium flavolapis* is the primary fungus strain trademarked by Nature's Fynd and also known as Fy™. The strain was discovered in 2009 in soil samples from the Yellowstone National Park in the United States. Nature's Fynd recently launched their first food products in the U.S. in 2021, a breakfast patty and cream cheese made from Fy. Mycelium fermentation has also been used to create one of the first whole cut meat replacements by U.S. based company, Meati Foods. They use a proprietary strain and utilize the fibrous network formed by the fungi's hyphae to mimic the familiar fibrous texture characteristic to most meat products.

While mycoprotein has been extremely promising in the search for alternative protein sources with considerably lower environmental impact and resource demands, one of the major concerns has been consumer acceptance due to concerns about mycotoxin production. While extensive toxicological work has been performed on the Quorn fungus, newer strains of fungi being used need to be evaluated for the same, which is time consuming.

10.3.2 Precision Fermentation

Ingredients produced using precision fermentation typically use an organism modified to efficiently produce specific compounds of interest at scale and in a cost-effective way (Teng et al., 2021). For example, leghemoglobin is a molecule derived from legume nodules and has properties similar to that of hemoglobin responsible for the meaty flavor and color of animal meat products. However, extracting leghemoglobin from legume nodules is costly and would require impractical amounts of starting material. To solve this problem, Impossible foods capitalized on the desirable properties of leghemoglobin by genetically engineering a yeast, *Pichia pastoris*, to efficiently produce leghemoglobin using precision fermentation. Such fermentation-based innovations are rapidly occupying a space in the food industry. Perfect Day is another company using fungal precision fermentation to make milk proteins (casein and whey), whereas the EVERY company (formerly known as Clara Foods) harnesses precision fermentation by modified yeasts to create animal protein replacements such as egg white protein. Precision fermentation offers a lot of flexibility in producing ingredients that are not only more cost-effective but also can be designed to have sensory appeal for alternative protein products. Finally, mycoprotein and precision fermentation-based products, unlike most other most novel innovations in the food space, face fewer challenges with consumer acceptance primarily due to consumers' familiarity with mushrooms as compared to protein derived from insects or algae.

10.4 Insects

Insects have been identified as future food and a sustainable source of protein (Parodi et al., 2018). They are included in this chapter for their potential as a sustainable food despite their not being plants. Insects are a highly diverse class of organisms leading to diversity in cuisine (Melgar-lalanne, 2019). They provide a highly efficient link for the development of circular food economies by transforming organic byproducts or waste into homogenous and stable biomass (Cadinu et al., 2020; Ojha et al., 2020). Insects have become a popular feedstock to supplement animal feed making the process more environmentally and economically efficient. The Black Soldier Fly alone has been studied as feed for swine (Veldkamp & Bosch, 2015), poultry (Cullere et al., 2016; Schiavone et al., 2017), and fish (Belghit et al., 2019; Irungu et al., 2018) with many promising results. Sánchez-Muros et al. (2016) previously summarized global utilization of insects as feed, showing increased adoption of these sustainable protein sources. While contributing to the sustainability of animal agriculture is an important goal, to maximize the sustainability of the entire system, direct consumption by humans is more efficient. This route will likely provide the greatest economic benefit to producers since human food typically sells at a higher price than animal feeds. Increasing demand of insects as human food and the displacement of less sustainable food sources is a goal shared by many in industry and research.

The western edible insect market is currently dominated by cricket-based products while a wide variety of whole insects are consumed globally. The global edible insect market is growing approximately 28% a year and is expected to reach 1.18 billion dollars globally in 2023 (Statista, 2019). Industrialization of insect foods is still developing which accounts for the rapid growth, along with a growing demand for protein-rich foods (Drewnowski et al., 2010). Traditionally, insects such as true bugs, caterpillars, beetles, ants, grasshoppers, and many others were harvested from the wild (van Huis & Oonincx, 2017). However, wild caught insects have drawbacks as a mechanism for increasing sustainability due to multiple factors including destruction of habitats, food safety, and scalability. Traditional insect cuisine is also associated with eating insects whole often after being cooked. Seeing whole insects on their plate is major turn off for many westerns as well as younger generations not accustomed to the traditional cuisine of their region. Forward thinking food developers and researchers have learned that the "ick" factor might be avoided by creating foods which do not resemble insects (Lammers et al., 2019; Mishyna et al., 2020; Sogari et al., 2018). This phenomenon might explain the early success of cricket powder, but other insects are emerging as well.

Edible insects are thought to be a mechanism for environmental sustainability in the food system. For this to occur, consumers must be willing to eat a variety of critters. While learning about insects' environmental benefits does increase consumers' willingness-to-eat (Kauppi et al., 2019; Verneau et al., 2016; Wendin & Nyberg, 2021), the nutritional quality of many insects will help establish a robust long-term market. When considering insect nutrition, it is difficult to comprehend the scope and diversity present within this emerging class of food. Multiple estimates suggest there are between 1,700 and 2,100 different species of edible insects in the world (Govorushko, 2019). This diversity is amplified further after considering life stage as some insects are edible throughout their life cycle. Different species and different life stages bring about a variety of nutritional profiles as well as different textural and flavor profiles. Generalizing is difficult and this topic has been reviewed in great detail over the years (Baiano, 2020; da Silva Lucas et al., 2020; Kouřimská & Adámková, 2016; Rumpold & Schlüter, 2013; van Huis, 2020). Insect protein, fat, carbohydrate, and micronutrient contents content can vary greatly among species and life stages while also being affected by cultivation conditions and diet. Many insects such as crickets, grasshoppers, and mealworms are actively being pursued for their high protein content. The salt content of many insects is one potential drawback in developed nations where salt intake has historically been beyond the needs of the population (He et al., 2019).

Aside from the "ick" factor and the potentially high salt content, other safety related concerns will be encountered. Fortunately for the promotion of entomophagy, there are no novel microbiological concerns. No insect-specific human pathogens have been identified in insects (Rumpold et al., 2017; Wade & Hoelle, 2019). This simple fact should provide comfort to food processors as they will not need to prepare for any additional pathogens during processing. (Sandrock et al., 2018) have shown known foodborne pathogens such as *Salmonella* and *Bacillus* make up a portion of the black soldier fly (BSFL) gut microbiota. These hazards should be treated the same as any other plant, fungi, or animal food sources. Bioaccumulation is another concern that has not shown to be a great risk (Erickson et al., 2004) and (Schlüter et al., 2017) suggest the BSFL, regardless of feedstock would not pose a serious risk due to minimal bioretention. Quality control techniques at rearing facilities have been implemented to reduce toxins or heavy metals entering animal feeds and are readily translated to human food operations (Barragan-Fonseca et al., 2017; van der Spiegel & Noordam, 2013).

Insects are a promising avenue to increase the global food systems sustainability. Traditional food sources including animals and staple crops have been identified for their high land, water, and carbon emissions (Smetana et al., 2021). Insects achieve greater efficiency by consuming organic materials that would otherwise be wasted; diverting them from the landfills and preventing the associated methane production in much smaller areas (Ojha et al., 2020). With their desirable nutritional profiles, low additional safety risk, and growing support; insects are primed to be an essential element of a global sustainable food industry.

10.5 Conclusions

The world is constantly changing; shifts in climate and geography naturally produce evolution of the life on Earth. Our current knowledge regarding climate change describes how human activity is accelerating changes in climate that are resulting in changes to regional geography and weather. These human-driven changes are occurring more rapidly than the natural ebbs and flows, putting many species and many humans in danger. The industrialization of food shares responsibility for this situation while having the tools to build more sustainable systems. There are two main areas of action that will be needed to produce a healthy plant and provide food security: (1) emission-reducing and (2) resilience-building actions. All changes to the food system will result in dietary changes on the consumer level. Encouraging and exploiting the most sustainable nutrient sources and ensuring consumer acceptance is essential for new systems. This chapter focused on algae, insects, and fungi which can serve as both emission reducers and resilience builders. Small land footprints are common among these emerging food sources which reduce emissions thorough allowing carbon sequestering forests to be grown instead. Reduced demand for land is also important for resilience as it can serve the growing population even as land becomes more and more scarce. These emerging sources are also high in quality protein which can help displace animal agriculture and potentially provide emissions reduction. Animal agriculture also lacks resiliency due to the high rates of disease and incredibly high demands for land and water. Transitioning from animal-based agriculture does provide challenges, especially from a consumer standpoint as many consumers have become accustomed to animal products. Research shows that education can help get consumers to try new things while appealing forms and flavors can increase liking. These alternative foods will not be adopted overnight. It is important that researchers continually develop novel products while considering the consumer and the sustainability within the system.

References

Afonso, N. C., Catarino, M. D., Silva, A. M. S., & Cardoso, S. M. (2019). Brown macroalgae as valuable food ingredients. In *Antioxidants* (Vol. 8(9)). MDPI. https://doi.org/10.3390/antiox8090365

Ahmad, M. I., Farooq, S., Alhamoud, Y., Li, C., & Zhang, H. (2022). A review on mycoprotein: History, nutritional composition, production methods, and health benefits. *Trends in Food Science and Technology, 121*(December 2021), 14–29. https://doi.org/10.1016/j.tifs.2022.01.027

Aschemann-Witzel, J., Gantriis, R. F., Fraga, P., & Perez-Cueto, F. J. (2021). Plant-based food and protein trend from a business perspective: markets, consumers, and the challenges and opportunities in the future. *Critical Reviews in Food Science and Nutrition, 61*(18), 3119–3128.

Baghel, R. S., Trivedi, N., Gupta, V., Neori, A., Reddy, C. R. K., Lali, A., & Jha, B. (2015). Biorefining of marine macroalgal biomass for production of biofuel and commodity chemicals. *Green Chemistry, 17*(4), 2436–2443.

Baiano, A. (2020). Edible insects: An overview on nutritional characteristics, safety, farming, production technologies, regulatory framework, and socio-economic and ethical implications. In *Trends in food science and technology* (Vol. 100, pp. 35–50). https://doi.org/10.1016/j.tifs.2020.03.040

Barragan-Fonseca, K. B., Dicke, M., & van Loon, J. J. A. (2017). Nutritional value of the black soldier fly (Hermetia illucens L.) and its suitability as animal feed – a review. *Journal of Insects as Food and Feed, 3*(2), 105–120. https://doi.org/10.3920/jiff2016.0055

Barros de Medeiros, V. P., da Costa, W. K. A., da Silva, R. T., Pimentel, T. C., & Magnani, M. (2021). Microalgae as source of functional ingredients in new-generation foods: Challenges, technological effects, biological activity, and regulatory issues. In *Critical reviews in food science and nutrition*. Bellwether Publishing. https://doi.org/10.1080/10408398.2021.1879729

Belasco, W. (1997). Algae burgers for a hungry world? The rise and fall of chlorella cuisine. In *Source: Technology and culture* (Vol. 38(3)) https://www.jstor.org/stable/3106856

Belghit, I., Liland, N. S., Gjesdal, P., Biancarosa, I., Menchetti, E., Li, Y., Waagbø, R., Krogdahl, Å., & Lock, E. J. (2019). Black soldier fly larvae meal can replace fish meal in diets of sea-water phase Atlantic salmon (Salmo salar). *Aquaculture, 503*(October), 609–619. https://doi.org/10.1016/j.aquaculture.2018.12.032

Bezner Kerr, R., Hasegawa, T., Lasco, R., Bhatt, I., Deryng, D., Farrell, A., Gurney-Smith, H., Ju, H., Lluch-Cota, S., Meza, F., Nelson, G., Neufeldt, H., & Thornton, P. (2022). Food, fibre, and other ecosystem products. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría,

M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate change 2022: Impacts, adaptation, and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. In Press.
Cadinu, L. A., Barra, P., Torre, F., Delogu, F., & Madau, F. A. (2020). Insect rearing: Potential, challenges, and circularity. In *Sustainability (Switzerland)* (Vol. 12(11)). MDPI. https://doi.org/10.3390/su12114567
Chew, K. W., Yap, J. Y., Show, P. L., Suan, N. H., Juan, J. C., Ling, T. C., Lee, D. J., & Chang, J. S. (2017). Microalgae biorefinery: High value products perspectives. *Bioresource Technology, 229*, 53–62. https://doi.org/10.1016/j.biortech.2017.01.006
Cotas, J., Leandro, A., Pacheco, D., Gonçalves, A. M. M., & Pereira, L. (2020). A comprehensive review of the nutraceutical and therapeutic applications of red seaweeds (Rhodophyta). In *Life* (Vol. 10(3)). MDPI AG. https://doi.org/10.3390/life10030019
Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food, 2*(3), 198–209. https://doi.org/10.1038/s43016-021-00225-9
Cullere, M., Tasoniero, G., Giaccone, V., Miotti-Scapin, R., Claeys, E., de Smet, S., & Dalle Zotte, A. (2016). Black soldier fly as dietary protein source for broiler quails: apparent digestibility, excreta microbial load, feed choice, performance, carcass and meat traits. *Animal, 10*(12), 1923–1930. https://doi.org/10.1017/s1751731116001270
da Silva Lucas, A. J., Menegon de Oliveira, L., da Rocha, M., & Prentice, C. (2020). Edible insects: An alternative of nutritional, functional and bioactive compounds. *Food Chemistry, 311*. https://doi.org/10.1016/j.foodchem.2019.126022
Dagevos, H. (2021). Finding flexitarians: Current studies on meat eaters and meat reducers. *Trends in Food Science and Technology, 114*, 530–539.
Drewnowski, A., Hanks, A. S., & Smith, T. G. (2010). International trade, food and diet costs, and the global obesity epidemic. IN: *Trade, food, diet and health: Perspectives and Policy Options*, 77–90.
Erickson, M. C., Islam, M., Sheppard, C., Liao, J., & Doyle, M. P. (2004). Reduction of Escherichia coli O157:H7 and salmonella enterica serovar Enteritidis in chicken manure by larvae of the black soldier fly. *Journal of Food Protection, 67*(4), 685–690.
Estell, M., Hughes, J., & Grafenauer, S. (2021). Plant protein and plant-based meat alternatives: Consumer and nutrition professional attitudes and perceptions. *Sustainability, 13*(3), 1478.
FAO. (2020). Emissions due to agriculture global, regional and country trends
Garza, D. A., & Program, A. S. G. C. (2005). *Common edible seaweeds in the Gulf of Alaska*. Alaska Sea Grant College Program.
Goldstein, B., Moses, R., Sammons, N., & Birkved, M. (2017). *Potential to curb the environmental burdens of American beef consumption using a novel plant-based beef substitute*, 1–17.
Gouveia, L., Batisa, A. P., Sousa, I., Raymundo, A., & Bandarra, N. M. (2008). *Food chemistry research developments*. Nova Science Publishers.
Govorushko, S. (2019). Global status of insects as food and feed source: A review. *Trends in Food Science and Technology, 91*, 436–445. https://doi.org/10.1016/j.tifs.2019.07.032
Grahl, S., Palanisamy, M., Strack, M., Meier-Dinkel, L., Toepfl, S., & Mörlein, D. (2018). Towards more sustainable meat alternatives: How technical parameters affect the sensory properties of extrusion products derived from soy and algae. *Journal of Cleaner Production, 198*, 962–971. https://doi.org/10.1016/j.jclepro.2018.07.041
Greene, J. M., Gulden, J., Wood, G., Huesemann, M., & Quinn, J. C. (2020). Techno-economic analysis and global warming potential of a novel offshore macroalgae biorefinery. *Algal Research, 51*. https://doi.org/10.1016/j.algal.2020.102032
Griffiths, M., Harrison, S. T. L., Smit, M., & Maharajh, D. (2016). Major commercial products from micro-and macroalgae. *Algae Biotechnology*, 269–300. www.made-in-china.com
Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B. L., Doelman, J. C., Fellmann, T., Kyle, P., Koopman, J. F. L., Lotze-Campen, H., Mason-D'Croz, D., Ochi, Y., Pérez Domínguez, I., Stehfest, E., Sulser, T. B., Tabeau, A., Takahashi, K., Takakura, J., van Meijl, H., et al. (2018). Risk of increased food insecurity under stringent global climate change mitigation policy. In *Nature climate change* (Vol. 8(8), pp. 699–703). Nature Publishing Group. https://doi.org/10.1038/s41558-018-0230-x
He, F. J., Brown, M., Tan, M., & MacGregor, G. A. (2019). Reducing population salt intake—an update on latest evidence and global action. In *Journal of clinical hypertension* (Vol. 21(10), pp. 1596–1601). Blackwell Publishing Inc. https://doi.org/10.1111/jch.13664
Irungu, F. G., Mutungi, C. M., Faraj, A. K., Affognon, H., Tanga, C., Ekesi, S., Nakimbugwe, D., & Fiaboe, K. K. M. (2018). Minerals content of extruded fish feeds containing cricket (Acheta domesticus) and black soldier fly larvae (Hermetia illucens) fractions. *International Aquatic Research, 10*(2), 101–113. https://doi.org/10.1007/s40071-018-0191-8
Kaori, O., & Connor. (2017). In A. Smith (Ed.), *Seaweed: A global history*. Reaktion Books Ltd.
Kauppi, S. M., Pettersen, I. N., & Boks, C. (2019). Consumer acceptance of edible insects and design interventions as adoption strategy. *International Journal of Food Design, 4*(1), 39–62. https://doi.org/10.1386/ijfd.4.1.39_1
Kouřimská, L., & Adámková, A. (2016). Nutritional and sensory quality of edible insects. In *NFS journal* (Vol. 4, pp. 22–26). Elsevier GmbH. https://doi.org/10.1016/j.nfs.2016.07.001
Koyande, A. K., Chew, K. W., Rambabu, K., Tao, Y., Chu, D.-T., & Show, P.-L. (2019). Microalgae: A potential

alternative to health supplementation for humans. *Food Science and Human Wellness, 8*(1), 16–24. https://doi.org/10.1016/j.fshw.2019.03.001

Lammers, P., Ullmann, L. M., & Fiebelkorn, F. (2019). Acceptance of insects as food in Germany: Is it about sensation seeking, sustainability consciousness, or food disgust? *Food Quality and Preference, 77*, 78–88. https://doi.org/10.1016/j.foodqual.2019.05.010

Lang, I., Hodac, L., Friedl, T., & Feussner, I. (2011). Fatty acid profiles and their distribution patterns in microalgae: A comprehensive analysis of more than 2000 strains from the SAG culture collection. *BMC Plant Biology, 11*. https://doi.org/10.1186/1471-2229-11-124

Magdugo, R. P., Terme, N., Lang, M., Pliego-Cortés, H., Marty, C., Hurtado, A. Q., Bedoux, G., & Bourgougnon, N. (2020). An analysis of the nutritional and health values of Caulerpa racemosa (Forsskål) and Ulva fasciata (Delile)—two chlorophyta collected from the Philippines. *Molecules, 25*(12). https://doi.org/10.3390/molecules25122901

Matos, Â. P. (2019). Microalgae as a potential source of proteins. In *Proteins: Sustainable Source, Processing and Applications*. https://doi.org/10.1016/b978-0-12-816695-6.00003-9

Matufi, F., & Choopani, A. (2020). Spirulina, food of past, present and future. *Health Biotechnology and Biopharma, 3*(4), 1–20. https://doi.org/10.22034/HBB.2020.26

Melgar-lalanne, G. (2019). Edible insects processing : Traditional and innovative technologies. *Comprehnsive Reviews in Food Science and Food Safety, 18*, 1166–1191. https://doi.org/10.1111/1541-4337.12463

Michel, F., Hartmann, C., & Siegrist, M. (2021). Consumers' associations, perceptions and acceptance of meat and plant-based meat alternatives. *Food Quality and Preference, 87*, 104063.

Mishyna, M., Chen, J., & Benjamin, O. (2020). Sensory attributes of edible insects and insect-based foods – future outlooks for enhancing consumer appeal. *Trends in Food Science and Technology, 95*(September 2019), 141–148. https://doi.org/10.1016/j.tifs.2019.11.016

Murphy, A. E., Anderson, I. C., & Luckenbach, M. W. (2015). Enhanced nutrient regeneration at commercial hard clam (Mercenaria mercenaria) beds and the role of macroalgae. *Marine Ecology Progress Series, 530*, 135–151. https://doi.org/10.3354/meps11301

Neupane, D., Adhikari, P., Bhattarai, D., Rana, B., Ahmed, Z., Sharma, U., & Adhikari, D. (2022). Does climate change affect the yield of the top three cereals and food security in the world? *Earth, 3*(1), 45–71. https://doi.org/10.3390/earth3010004

Ojha, S., Bußler, S., & Schlüter, O. K. (2020). Food waste valorisation and circular economy concepts in insect production and processing. In *Waste management* (Vol. 118, pp. 600–609). Elsevier Ltd. https://doi.org/10.1016/j.wasman.2020.09.010

Onwezen, M. C., Bouwman, E. P., Reinders, M. J., & Dagevos, H. (2021). A systematic review on consumer acceptance of alternative proteins: Pulses, algae, insects, plant-based meat alternatives, and cultured meat. In *Appetite* (Vol. 159). Academic Press. https://doi.org/10.1016/j.appet.2020.105058

Parodi, A., Leip, A., de Boer, I. J. M., Slegers, P. M., Ziegler, F., Temme, E. H. M., Herrero, M., Tuomisto, H., Valin, H., van Middelaar, C. E., van Loon, J. J. A., & van Zanten, H. H. E. (2018). The potential of future foods for sustainable and healthy diets. *Nature Sustainability, 1*(12), 782–789. https://doi.org/10.1038/s41893-018-0189-7

Renaud, S. M., & Luong-Van, J. T. (2006). Seasonal variation in the chemical composition of tropical Australian marine macroalgae. *Journal of Applied Phycology, 18*(3–5), 381–387. https://doi.org/10.1007/s10811-006-9034-x

Rumpold, B. A., & Schlüter, O. K. (2013). Nutritional composition and safety aspects of edible insects. In *Molecular nutrition and food research* (Vol. 57(5), pp. 802–823). https://doi.org/10.1002/mnfr.201200735

Rumpold, B., Holzhauser, T., Roth, A., Schl, O., Quasigroch, W., Vogel, S., Heinz, V., Henry, J., Bandick, N., Kulling, S., Knorr, D., Steinberg, P., & Engel, K. (2017). Safety aspects of the production of foods and food ingredients from insects. *Molecular Nutrition & Food Research, 1600520*(61), 1600520. https://doi.org/10.1002/mnfr.201600520

Sánchez-Muros, M. J., Barroso, F. G., & de Haro, C. (2016). Brief summary of insect usage as an industrial animal feed/feed ingredient. In *Insects as sustainable food ingredients* (pp. 273–309). Elsevier. https://doi.org/10.1016/b978-0-12-802856-8.00010-7

Sandrock, C., Lievens, B., Claes, J., Frooninckx, L., Wynants, E., Van Miert, S., Depraetere, S., Van Campenhout, L., Van Schelt, J., De Smet, J., Verreth, C., Crauwels, S., & Wohlfahrt, J. (2018). Assessing the microbiota of black soldier Fly larvae (*Hermetia illucens*) reared on organic waste streams on four different locations at laboratory and large scale. *Microbial Ecology, 77*, 913–930. https://doi.org/10.1007/s00248-018-1286-x

Schiavone, A., de Marco, M., Martínez, S., Dabbou, S., Renna, M., Madrid, J., Hernandez, F., Rotolo, L., Costa, P., Gai, F., & Gasco, L. (2017). Nutritional value of a partially defatted and a highly defatted black soldier fly larvae (Hermetia illucens L.) meal for broiler chickens: Apparent nutrient digestibility, apparent metabolizable energy and apparent ileal amino acid digestibility. *Journal of Animal Science and Biotechnology, 8*(1), 1–9. https://doi.org/10.1186/s40104-017-0181-5

Schlüter, O., Rumpold, B., Holzhauser, T., Roth, A., Vogel, R. F., Quasigroch, W., Vogel, S., Heinz, V., Jäger, H., Bandick, N., Kulling, S., Knorr, D., Steinberg, P., & Engel, K. H. (2017). Safety aspects of the production of foods and food ingredients from insects. *Molecular Nutrition & Food Research, 61*(6), 1–14. https://doi.org/10.1002/mnfr.201600520

Smetana, S., Spykman, R., & Heinz, V. (2021). Environmental aspects of insect mass production.

Journal of Insects as Food and Feed, 7(5), 553–571. https://doi.org/10.3920/JIFF2020.0116

Smith, B. (2019). *Eat like a fish: My adventures farming the ocean to fight climate change* (1st ed.). Penguin Random House.

Sogari, G., Menozzi, D., & Mora, C. (2018). Sensory-liking. *Expectations and Perceptions of Processed and Unprocessed Insect Products, 9*(4), 314–320.

Statista, Edible Insects - Statistics & Facts, *Stastita.com*, https://www.Statista.Com/Topics/4806/Edible-Insects/#topicHeader__wrapper (2019).

Subhadra, B., & Grinson-George. (2011). Algal biorefinery-based industry: An approach to address fuel and food insecurity for a carbon-smart world. *Journal of the Science of Food and Agriculture, 91*(1), 2–13. https://doi.org/10.1002/jsfa.4207

Suparmaniam, U., Lam, M. K., Uemura, Y., Lim, J. W., Lee, K. T., & Shuit, S. H. (2019). Insights into the microalgae cultivation technology and harvesting process for biofuel production: A review. In *Renewable and sustainable energy reviews* (Vol. 115). Elsevier Ltd. https://doi.org/10.1016/j.rser.2019.109361

Talebi, A. F., Mohtashami, S. K., Tabatabaei, M., Tohidfar, M., Bagheri, A., Zeinalabedini, M., Hadavand Mirzaei, H., Mirzajanzadeh, M., Malekzadeh Shafaroudi, S., & Bakhtiari, S. (2013). Fatty acids profiling: Selective criterion for screening microalgae strains for biodiesel production. *Algal Research, 2*(3), 258–267. https://doi.org/10.1016/j.algal.2013.04.003

Teng, T. S., Chin, Y. L., Chai, K. F., & Chen, W. N. (2021). Fermentation for future food systems. *EMBO Reports, 22*(5), 1–6. https://doi.org/10.15252/embr.202152680

Teoh, M.-L., Chu, W.-L., Marchant, H., & Phang, S.-M. (2004). Influence of culture temperature on the growth, biochemical composition and fatty acid profiles of six Antarctic microalgae. *Journal of Applied Phycology, 16*, 421–430. https://doi.org/10.1007/s10811-005-5502-y

Thrupp, L. A. (2000). Linking agricultural biodiversity and food security: The valuable role of agrobiodiversity for sustainable agriculture. *International Affairs, 76*(2), 265–281. https://doi.org/10.1111/1468-2346.00133

Torres-Tiji, Y., Fields, F. J., & Mayfield, S. P. (2020). Microalgae as a future food source. In *Biotechnology advances* (Vol. 41). Elsevier Inc. https://doi.org/10.1016/j.biotechadv.2020.107536

United Nations. (2019). Probabilistic population projections rev. 1 based on the world population prospects 2019. *United Nations, 2019*.

van der Spiegel, M., & Noordam, M. Y. (2013). *Safety of novel protein sources (insects , microalgae, seaweed, duckweed, and rapeseed) and legislative aspects for their application in food and feed production* (Vol. 12, pp. 662–678). https://doi.org/10.1111/1541-4337.12032

van Huis, A. (2020). Nutrition and health of edible insects. In *Current opinion in clinical nutrition and metabolic care* (Vol. 23(3), pp. 228–231). Lippincott Williams and Wilkins. https://doi.org/10.1097/MCO.0000000000000641

van Huis, A., & Oonincx, D. G. A. B. (2017). The environmental sustainability of insects as food and feed. A review. In *Agronomy for sustainable development* (Vol. 37(5)). Springer. https://doi.org/10.1007/s13593-017-0452-8

Varela, P., Arvisenet, G., Gonera, A., Myhrer, K. S., Fifi, V., & Valentin, D. (2022). Meat replacer? No thanks! The clash between naturalness and processing: An explorative study of the perception of plant-based foods. *Appetite, 169*, 105793.

Veldkamp, T., & Bosch, G. (2015). Insects - a protein rich feed ingredient in pig and poultry diets. *Animal Frontiers, 5*(2), 45–50. https://doi.org/10.2527/af.2015-0019

Verneau, F., la Barbera, F., Kolle, S., Amato, M., del Giudice, T., & Grunert, K. (2016). The effect of communication and implicit associations on consuming insects: An experiment in Denmark and Italy. *Appetite, 106*, 30–36. https://doi.org/10.1016/j.appet.2016.02.006

Wade, M., & Hoelle, J. (2019). A review of edible insect industrialization: Scales of production and implications for sustainability. In *Environmental research letters* (Vol. 15(12)). IOP Publishing Ltd. https://doi.org/10.1088/1748-9326/aba1c1

Wang, X., Hua, F., Wang, L., Wilcove, D. S., & Yu, D. W. (2019). The biodiversity benefit of native forests and mixed-species plantations over monoculture plantations. *Diversity and Distributions, 25*(11), 1721–1735. https://doi.org/10.1111/ddi.12972

Wang, Y., Tibbetts, S. M., & McGinn, P. J. (2021). Microalgae as sources of high-quality protein for human food and protein supplements. *Food, 10*(12), 3002. https://doi.org/10.3390/foods10123002

Wells, M. L., Potin, P., Craigie, J. S., Raven, J. A., Merchant, S. S., Helliwell, K. E., Smith, A. G., Camire, M. E., & Brawley, S. H. (2017). Algae as nutritional and functional food sources: Revisiting our understanding. In *Journal of applied phycology* (Vol. 29(2), pp. 949–982). Springer. https://doi.org/10.1007/s10811-016-0974-5

Wendin, K. M., & Nyberg, M. E. (2021). Factors influencing consumer perception and acceptability of insect-based foods. In *Current opinion in food science* (Vol. 40, pp. 67–71). Elsevier Ltd. https://doi.org/10.1016/j.cofs.2021.01.007

Wiebe, M. (2002). Myco-protein from fusarium venenatum: A well-established product for human consumption. *Applied Microbiology and Biotechnology, 58*(4), 421–427. https://doi.org/10.1007/s00253-002-0931-x

Xia, B., & Abbott, I. A. (1987). *Edible seaweeds of China and their place in the Chinese diet. Economic Botany* (Vol. 41(3)). Springer.

11 Understanding New Foods: Upcycling

Miranda Mirosa and Phil Bremer

Abstract

Investing in food waste reduction initiatives and finding innovations that unlock the potential of food waste makes great sense from an economic, social, and environmental perspective. One food waste prevention action that is gaining considerable momentum in the food production and manufacturing sectors is upcycling food. Upcycled foods are made from ingredients that would otherwise have ended up in a food waste destination. They are value-add products. This chapter introduces the latest upcycling marketplace trends and companies in the market selling upcycled products before taking a further look at upcycling in a country case study context: New Zealand. Given, ultimately, the success or failure of this sector will depend on consumer acceptability of these new products, results from a consumer study consisting of four focus groups (total n=29) and a nationally representative survey of 1000 consumers were carried out to assess consumers' perceptions of foods derived from supermarket surplus bread. The results of this study indicate that there appears to be sufficient demand in New Zealand to consider upcycling as an idea with exciting market potential.

11.1 Introduction. The Food Waste Issue

Food waste is a pressing global issue with significant environmental and social implications. Approximately 40 percent of food produced for human consumption is lost or wasted globally; This is believed to be around 2.5 billion tonnes each year (WWF, 2021) and is occurring during a time when perversely a projected 720 to 811 million people in the world face hunger (FAO et al., 2021). The environmental impact of this wasted food is also considerable, as it generates 8–10% of global greenhouse gas emissions annually (UNEP, 2021). Therefore, according to Project Drawdown, preventing food waste is one of the most effective solutions to global warming (Project Drawdown Solutions 2020). Reducing food waste also presents an enormous economic

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Miranda and Phil are Steering Committee Leads of the University of Otago Food Waste Innovation Research Theme, which measures food waste, develops reduction strategies, applies innovative technology, and works to modify producer and consumer behavior. As New Zealand's leading provider of food waste-related research, this group of interdisciplinary researchers harnesses the best scientific expertise at the University and nationwide to provide effective solutions to food waste problems.

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opportunity, given that globally, the financial cost of wasting food is estimated to be approximately USD 1 trillion per year (FAO, 2014). This cost increases to 2.6 trillion USD per year if the full costs of food wastage (i.e., including USD 700 billion of environmental costs and USD 900 billion of social costs) are included (FAO, 2014). According to the food waste non-profit Rethink Food Waste Through Economics and Data (ReFED), an annual investment of USD 14 billion over the next ten years can reduce food waste by 50% each year and result in an annual net financial benefit of USD 73 billion (a sizeable one-to-five return on investment). Therefore, investing in food waste reduction initiatives and finding innovations that unlock the potential of food waste makes great sense from an economic, social, and environmental perspective.

11.2 Preventing Food Loss and Waste

Food waste is generated at each stage of the food supply chain, including during the production, handling and storage, processing and packaging, distribution and in retail, and by consumers in their households. In developed nations attention has been given to finding solutions to the food waste problems in the latter stages of the food supply chain, however comparatively, little attention has been given to developing solutions at the production and manufacturing stages.

Reduction of food waste should be prioritized according to WRAP's internationally recognized food use hierarchy (WRAP, 2021). This food and drink material hierarchy sets out steps for dealing with waste to minimize its impact on the environment. The preferable option is to ideally prevent waste from occurring in the first place. Then, the impact of any surplus food that is still produced can be reduced by redistributing it for human consumption or by sending it for animal feed. Ultimately, the key message is that efforts to keep food as food are essential.

11.2.1 An Exciting Solution: Keeping Food as Food Through Upcycling

One food waste prevention action that is gaining considerable momentum in the food production and manufacturing sectors is upcycling food. Upcycled foods are made from ingredients that would otherwise have ended up in a food waste destination. They are value-add products. A team of international experts from Harvard Law School, World Wildlife Fund, Upcycled Food Association, and others officially defined upcycled food in 2020 for use in policy, research, and more as 'Upcycled foods use ingredients that otherwise would not have gone to human consumption, are procured and produced using verifiable supply chains, and have a positive impact on the environment (Spratt et al., 2021). Although food manufacturers are used to finding value for sidestreams and by-products, upcycled food, as per the above definition, is widely considered a new food category alongside conventional and organic foods (Bhatt et al., 2018). It's an innovative approach to food waste because it is the first consumer product-based solution, making it highly scalable and economically sustainable.

A report produced by Future Market (2022) valued the global products from the food waste market to be worth USD 52.91 billion in 2022 with an expected compound annual growth rate of 4.6% suggesting that it could reach USD 83.26 billion by 2032 (Future Market Insights, 2022). Upcycling has been touted as a major food trend that will define the industry by a number of market observers including the Food Network Magazine, Whole Foods, Food Business News, Future Market Insights, and CBS News, among others. According to food Artificial Intelligence company, Spoonshot, interest in upcycling grew by 128% across business media from 2018–2019 (Spoonshot, 2019).

The Upcycled Food Association which was created in 2019 with members and associate members worldwide, is a critical driving force behind this new movement. With a focus on research, strategy, networking, and policy advocacy, the Association works to attract more investment to the upcycled industry, improve the upcycled business network, improve the upcycled supply chain, and increase consumer demand for upcycled products (https://www.upcycledfood.org/). As an example of their work, the Association supports its businesses through its Upcycled Food Digital Marketing Toolkit, which contains a guide to upcycled food storytelling and marketing.

In 2021, it became possible to buy food with an Upcycled Certified™ label. This new standard which identifies authentic upcycled foods is administered by the third-party certification body, Where Food Comes From, which is the world's first third-party certification program for upcycled food ingredients and products. A complete list of certified upcycled products can be found at: https://www.upcycledfood.org/upcycled-certified-products. Although the program was less than a year old at the time of the writing of this chapter, early reports show that the impact of Upcycled Certified™ on food waste prevention is much higher than initially anticipated, with over 140 products and ingredients having achieved the certification by January 2022 (Waste 360, 2022). Early market research on consumer acceptability of the certificate has reported that over half of consumers are more likely to buy after seeing the Upcycled Certified™ mark on the product (Mattson, 2021).

11.2.2 Companies in the Market Selling Upcycled Products

Europe and North America are the major regional markets for products from food waste, with the UK and the US, in particular, starting to see the beginning of a massive swell of adoption and promotion of upcycled products by retailers propelling market growth (Future Market Insights, 2022). For example, estimates are that in 2021, there were already over 400 upcycled products in the US marketplace, and Moms, a retail chain with about 20 stores on the East Coast, had dedicated upcycled food end caps in all their stores (https://www.upcycledfood.org/). While upcycled foods are appearing in all product categories, two of the most important industries are beverage processing and bakery (Future Market Insights, 2022).

Vanguard company ReGrained (https://www.regrained.com/) is an ingredient platform that has been at the forefront of the upcycling movement. A couple of home brewers formed the company as a means to using leftover grain from the beer brewing process. The company uses a patented technology, co-created with the US Department of Agriculture, to leverage a thermo-mechanical process to stabilize and dehydrate the wet grain consistently in a gentle, energy/cost-efficient, and food-safe way. The resulting SuperGrain+® upcycled ingredient, which is high in plant protein and dietary fiber, is sold as a diverse wholesale ingredient in the B2B market for a wide variety of commercial applications. The company's innovation showcase range features SuperGrain+® in savory puffs, nutrition bars, and artisan pasta.

Another example of an innovative company is CaPao, whose Upcycled Certified™ plant-powered snack range uses parts of the cacaofruit that traditionally were discarded (about 70% of the fruit) after cacao beans had been extracted for chocolate production. CaPao take the sweet, zesty pulp and combine it with nuts, seeds, and other fruits to create vegan-friendly, non-GMO, gluten-free snacks. Their snack product combining oats and puffed quinoa was listed in 2021 by Men's Health magazine as one of the 20 healthiest new snacks on the market that year.

Upcycling is a burgeoning industry with the companies creating upcycled food products ranging from small startups to large global brands. Other companies selling Upcycled Certified™ ingredients and products include, but are not limited to, The Spare Food Co., Blue Stripes Urban Cacao, Good Sport Nutrition, Agricycle, Super Frau, Bevea Coffee & Cascara, Grain4Grain, impASTA! Inc., Del Monte Foods, Inc., Reveal Hidden Gems Beverage Company, Matriark Foods, Chia Smash, Imperfect Foods, Lost and Found Distillery, Pulp Pantry, Renewal Mill, and Take Two. These companies are making an impact on food waste reduction, as illustrated by the following quote from co-founder and COO of Renewal Mill, who take the byproducts from the making of plant-based milk and turns them into a high fiber, gluten-free flour: *"In 2020, we diverted 100,000 lbs of food waste from plant-based milk, and because we sell bulk ingredients as well as final CPG products, 100% of that was turned into products sold"*.

11.2.3 A Further Look at Upcycling in a Case Study Context: New Zealand

As of the start of 2022, there is only a handful of commercially available upcycled food products in the New Zealand market that meet the official definition of upcycled foods. Products include upcycled grain crackers (from the company Rutherford & Meyer), pet food products (e.g., from producers such as Deja and Perfect Delifresh), and upcycled alcoholic beverages (e.g., from Dunedin Craft Distillers). The best-known company in this space is Citizen Collective (https://citizen.co.nz/), whose craft brewers use rescued unsold bread to make its ferments, then put beer byproducts (i.e., spent-grain flour) back into bread production to make sourdough loaves. The company also produces other products, including a Piquette using leftover winemaking grapes and a cheery bomb cider made with rescued cherries.

Supporting the development of the nascent upcycling industry in New Zealand are R&D organizations and innovation agencies like the Bioresource Processing Alliance (https://bioresourceprocessing.co.nz/), Callaghan Innovation (https://www.callaghaninnovation.govt.nz/), and Venture Timaru's Sustainable is Attainable Programme (https://www.vtdevelopment.co.nz). Another group working in this upcycled space is the University of Otago Food Waste Innovation Research Theme (https://foodwaste-otago.org/). The group harnesses the best scientific expertise to solve New Zealand's food waste problems. Over 50 investigators from across New Zealand's research institutes are engaged with the Theme, and over 200 members of the public are subscribed to the mailing list. The Theme has three subthemes: (1) Metrics and Management, which is about understanding how much food is being wasted, where it is being wasted, and its social, economic, and environmental impacts; (2) Technical Innovations, which is using the latest science and technology to provide food waste solutions; and (3) Social Innovations, which is using behavioral science to understand the drivers responsible for food waste to make recommendations on minimization initiatives. Spanning across all three areas is a dedicated Upcycled Food Lab, launched in 2021. Since then, Upcycled Food Lab researchers have conducted various projects. Working with upcycled company Citizen Collective, the maximum amount of bread that could be substituted into an excellent tasting beer was determined without adversely impacting on its character. Based on a series of product development trials, a 'how-to-guide' for homebrewers was developed that described how home brewers could replace 50% of the malt they traditionally used in their brews with bread. Per 500 ml of beer produced, 4.75 slices of bread are saved using this recipe. The bread-to-beer step-by-step homebrewer recipes has been made available to the public and can be found on the Theme's online Resource Hub. Some of the University's undergraduate students have equally been busy cooking up an upcycled storm in the Lab. For example, three third-year students co-founded 'Reshined Roots,' a startup working on upcycling 'ugly' carrots into tasty, crispy snacks. The trio were finalists of Start-Up Dunedin's Audacious program, which helps facilitate turning ideas of young entrepreneurs into reality.

As well as technical innovations in the Lab, the University's Upcycled Team are always busy on several other fronts. They have run a series of public engagement-type events to help educate the public on the benefits of upcycled foods. At the 2021 International Science Festival, they ran an upcycled dining experience collaborating with Everybody Eats, a social dining pay-as-you-feel dining concept with restaurants in Auckland and Wellington (https://everybodyeats.nz/). Among the three courses (all made by top chefs from surplus food) were products developed by their

Upcycled Lab. Throughout the evening, experts from the Food Waste Innovation research theme talked to guests about the issue of food waste and the science behind the upcycled products they were sampling.

But it's not just the public that needs to be educated about upcycling. It's the food industry and upcycling startups as well. One of the projects recently completed was to conduct interviews with category managers at supermarkets to understand their perceptions about upcycled foods and the associated decision-making processes which influence whether these products are stocked (Thorsen et al., 2021). This information is valuable as these category managers are the gatekeepers to retail shelves. The results provided insights into the barriers and opportunities for suppliers and manufacturers of upcycled food. Key recommendations for manufacturers included the need for an innovative unique product offering, and to be able to demonstrate to category managers a clear marketing plan as to how the product's 'story' will be communicated to customers.

11.2.4 Consumer Acceptability of Upcycled Foods

Of course, manufacturers can produce the best innovative products and even convince retailers to stock them; however, ultimately, the success or failure of this sector will depend on consumer's acceptability of these new products. Globally, the number of studies investigating various aspects of public acceptability of upcycled food is growing. There are broad reviews of what we know about upcycled food from a consumer perspective (Aschemann-Witzel & Stangherlin, 2021), as well as more specific in-depth studies that investigate different aspects such as if a logo can increase acceptance of upcycled foods (Bhatt et al., 2021a), the effect of nutritional and environmental information on the value food products containing upcycled ingredients (Asioli & Grasso, 2021), the role of transparency Peschel & Aschemann-Witzel (2020), and the role of pricing (Bhatt et al., 2021b). Market studies have provided insight to manufacturers on how to position upcycled foods to different generations (Zhang et al., 2021), providing tailored insight into specific segments such as Millennials (Coderoni & Perito, 2021). Some of the studies use an actual upcycled product to determine consumer preference, for example, Grasso and Asioli (2020) who determine choices for upcycled ingredients utilizing a case study with biscuits, while many other studies rely on hypothetical products and process definitions to investigate more general perceptions (Goodman-Smith et al., 2021).

Many of the abovementioned studies consider upcycling as a pretty broad category, including the use of byproducts/side streams and unmarketable wonky produce. Hence the University of Otago Food Waste Innovations Research Team saw value in looking closer at consumer perceptions of just one specific upcycled 'category'; those made by taking food waste off the supermarket shelf and reincorporating it back into the food system for later consumption. The study, conducted by two postgraduate research students (Bennett, 2019; Prendergast, 2019), also aimed to profile the consumers who would be most receptive to this type of upcycled food. A brief summary of the study design and results follows.

Four focus groups (total n = 29) and a nationally representative survey of 1,000 consumers were carried out to assess consumers'perceptions of foods derived from supermarket surplus. The focus group and the survey introduced the concept of upcycling bread to explain the idea. The description explained the process of upcycling supermarket waste, where foods reaching the end of their shelf-life are sent back to a processing facility to be then turned into a new product that is sold back to the supermarket. Bread was used as the example as high quantities of bread are currently being produced and wasted in supermarkets, and it was of the commercial interest of the company sponsoring the research.

Understanding respondents' initial reaction is crucial in product concept testing as it provides a good indicator of whether a particular product will stand out in the market. In summary, most respondents (80%) viewed upcycling supermarket waste as a unique concept stating that the idea was 'different' or 'very different.' These responses indicated that the proposed concept is different enough from existing solutions to be marketed as novel in the marketplace. The majority (63%) of respondents' initial reactions to the idea of upcycled supermarket foods were 'positive,' with a significant proportion (39%) having a 'somewhat positive' initial reaction. Respondents largely agreed with the statements 'I think the concept is exciting and has lots of potentials' (68% 'strongly agreed' or 'agreed') and that 'Reformulated products from supermarket end of shelf-life products appeal to me as they will be more environmentally friendly' (76% 'strongly agreed' or 'agreed').

When respondents were asked in a free-text comment box 'What do you like most about the concept?' the most frequently used terms included "wastage," "reduces," "recycling," "environment," "landfill," and "new" (Fig. 11.1). Interestingly, respondents also mentioned benefits to the economy (e.g., "*It's another manufacturing opportunity which provides more jobs*"). They also made a note of the fact they liked the fact that businesses were doing their part to fight food waste (e.g., "*Makes me feel light the big companies are finally getting their priorities right*").

When respondents were then asked, 'what do you like least about the concept?' the most frequently used terms included "afraid" and "cheap" (Fig. 11.2). Respondents reported, *"I'm afraid that this food could contain artificial chemical and ingredients,"* that *"the idea of old food being turned into new food just makes me feel queasy,"* and *"this sort of product will be seen as second-rate food and fit only for poor people."* Hence, manufacturers will need to develop trust and understanding of the processing of upcycled food amongst consumers, given consumers were reportedly still a little apprehensive about the safety, hygiene, and quality of products upcycled from product returned from supermarkets. Assurances and independent certifications (such as the Upcycled Certified™ label) will be critical to ensure that in the minds of consumers, this isn't *"just another opportunity for supermarkets to increase profits further."* A surprisingly common concern was that there could be negative social consequences to upcycling, i.e., that upcycling supermarket surplus could hurt the foodbanks who currently receive this product (e.g., *"Food banks for the needy will suffer"*).

A cluster analysis, which groups participants so that participants in the same groups (clusters) are more similar than those in other groups, was used to investigate potential market segments. Two clusters were found: cluster 1 (Anti-Upcycling) and cluster 2 (Pro-Upcycling) (Fig. 11.3). As the name suggests, the Anti-Upcyclers were more against the concept of foods made from upcycled products, less environmentally concerned, and more concerned about the safety and the risk of foods that are upcycled from supermarkets waste. Only weak relationships were found between demographic variables and clusters with a higher proportion of 'Pro-Upcyclers married with children (65.2%) than 'Anti-upcycling' (34.8%).

While the survey revealed the abovementioned individual-level factors determining consumer acceptance of supermarket upcycled food the focus groups permitted further insight into other types of factors that were also influencing consumer acceptance. Regarding product-related factors, the preference appeared to be for upcycled products to be disconnected from the raw material. So, for example rather than upcycling a surplus bread product into another loaf of bread the preference was for this to be turned into something in a distinct product category (e.g., beer). If the products were going to be sold as the same product type, then it would be beneficial to have added benefits such as fortification. Also, if it was going to be turned back into the same sort of product, then there was a feeling that this shouldn't be marketed or sold next to *"fresh"/ original product as this could make it appear inferior in comparison."* Product congruency was deemed necessary–e.g., upcycled products should have sustainable packaging and a minimal carbon footprint. Focus groups participants also discussed several contexts/communication-related factors that helped determine acceptance of supermarket upcycling. All participants

Fig. 11.1 Word cloud based on what consumers most like about the concept of upcycling supermarket waste. The larger the font, the more frequently the word was mentioned

Fig. 11.2 Word cloud based on what consumers like least about the concept of upcycling supermarket waste. The larger the font, the more frequently the word was mentioned

believed that the origin of the food needed to be clearly stated. There was a lot of discussion around the need to consider terminology and to message carefully. *"I think the overall concept is really good - if it goes ahead, I would just make sure the terms used to the public are understandable and will evoke the necessary emotion/response, i.e., not 're-purposed waste' on it."* Upcycled products were perceived as having higher 'other-benefits' than 'self-benefits,' so considering this in product promotions would be important. There was agreement that it would make sense initially for manufacturers and retailers to use novelty as a selling point for these products.

In conclusion, the results of this study (and the Food Waste Innovation Group's other subsequent consumer insight studies that have likewise focused on the New Zealand consumer (Goodman-Smith et al., 2021, 2022) indicate that

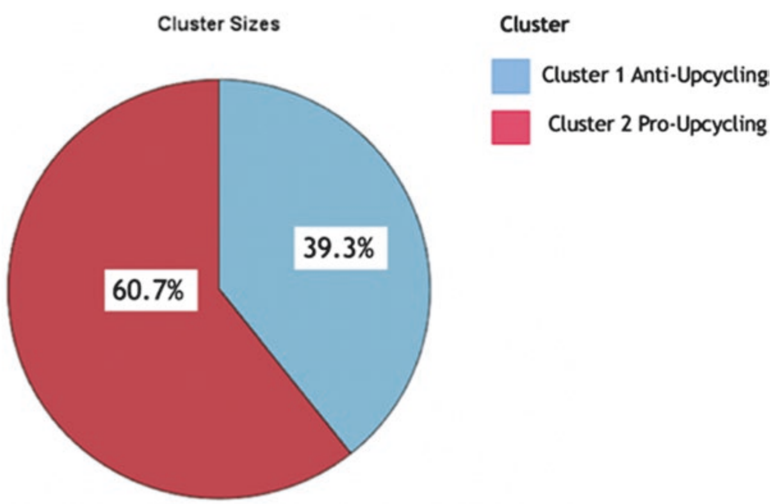

Fig. 11.3 Pie graph of the results from the two-step cluster analysis

there appears to be sufficient demand in New Zealand to consider upcycling as an idea with exciting market potential. One of the things the Research Team has done with their Theme's Resource Hub is to create a series of talking abstracts/project overviews where the researchers explain the findings of their work in an easily understandable way. So, for readers that would like to learn more about these findings but don't want to wade through the academic papers, this is a great way to learn more.

11.3 Next Steps. Paving the Way for an Upcycled Future

As upcycling becomes more accepted, the next goal will be to scale up the processes and build a secure infrastructure. It is not wise to underestimate this challenge; KPMG recently highlighted some of these challenges in their 2021 agribusiness report (KPMG Agribusiness Agenda, 2021, pg. 30) *"There is a lack of innovative businesses looking to create new markets for good quality, fresh and edible food that doesn't meet the visual grade for retailers. Setting up these businesses in NZ is expensive, scaling up is challenging, regulation is stifling, and the language 'food waste'puts consumers off the product… If we changed the conversation to upcycled foods and established standards so that entrepreneurs could gain credit for their impact, we might unlock a food system revolution!"*

There is something for everybody to do to tap into new opportunities to establish upcycled brands and processes. The government needs to support the sector, given it is still at an introductory level, so co-funding and support are required. Manufacturers should continue experimenting to find new ways to convert underused products into marketable upcycled products. They should also work towards certification for these products and help raise awareness about the environmental and societal benefits of these products specific to the consumer's values. Retailers need to start carrying more upcycled products, educate shoppers, and consider soft launches including in-store tastings of new products. Researchers must focus on solving R&D challenges and gain deeper insights into consumer behavior. There is a particular need for Life Cycle Assessment research so manufacturers can further validate that an upcycled product is better than the conventional from both a waste and emissions standpoint. And consumers must vote with their wallets and buy upcycled products as they become available to ensure that they become economically viable and mainstream.

Before concluding, it seems obvious, yet necessary, to make the point that upcycling alone is, of course, not going to save the world. Still, it will help, and food waste experts consider it a serious weapon in the global war on food waste. So, let's all raise an upcycled glass of bread-waste beer to that. "Cheers!"

References

Aschemann-Witzel, J., & Stangherlin, I. D. C. (2021). Upcycled byproduct use in Agri-food systems from a consumer perspective: A review of what we know, and what is missing. *Technol Forecast Soc Chang, 168*, 120749.

Asioli, D., & Grasso, S. (2021). Do consumers value food products containing upcycled ingredients? The effect of nutritional and environmental information. *Food Qual Prefer, 91*, 104194.

Bennett, M. (2019). *New Zealand Consumers' perceptions of new food types: a focus group study*. MAppSC research project, University of Otago, New Zealand.

Bhatt, S., Lee, J., Deutsch, J., Ayaz, H., Fulton, B., & Suri, R. (2018). From food waste to value-added surplus products (VASP): consumer acceptance of a novel food product category. *J Consum Behav, 17*, 57–63.

Bhatt, S., Ye, H., Deutsch, J., Jeong, H., Zhang, J., & Suri, R. (2021a). Food Waste and upcycled foods: Can a logo increase acceptance of upcycled foods? *J Food Prod Mark, 27*(4), 188–186.

Bhatt, S., Deutsch, J., & Suri, R. (2021b). Differentiating Price sensitivity from willingness to pay: Role of pricing in consumer acceptance of upcycled foods. *J Food Prod Mark*, *27*(7), 331–339.

Coderoni, S., & Perito, M. A. (2021). Approaches for reducing wastes in the agricultural sector. An analysis of Millennials' willingness to buy food with upcycled ingredients. *Waste Manag, 126*, 283–290.

FAO, IFAD, UNICEF, WFP and WHO. (2021). *The State of Food Security and Nutrition 2021: Transforming food systems for food security, improved nutrition and affordable healthy diets for all*. https://www.fao.org/publications/sofi/2021/en/. Accessed February 1, 2022.

FAO-Food and Agricultural Organisation. (2014). *Food wastage footprint full-cost accounting*. https://www.fao.org/nr/sustainability/food-loss-and-waste/en/. Accessed February 1, 2022.

Future Market Insights. (2022). *Products from food waste market*. https://www.futuremarketinsights.com/reports/products-from-food-waste-market. Accessed February 1, 2022.

Goodman-Smith, F., Bhatt, S., Moore, R., Mirosa, M., Ye, H., Deutsch, J., & Suri, R. (2021). Retail potential for upcycled foods: Evidence from New Zealand. *Sustainability, 13*(5), 2624.

Goodman-Smith, F., Bhatt, S., Ye, H., Grasso, S., Deutsch, J., Suri, R., & Mirosa, M. (2022). *A case of upcycled food and beverage: Will consumers accept upcycled craft beer and how can such products be effectively promoted?* Unpublished: Under Review.

Grasso, S., & Asioli, D. (2020). Consumer preferences for upcycled ingredients: a case study with biscuits. *Food Qual Prefer, 84*, 103951.

KPMG Agribusiness Agenda. (2021). https://home.kpmg/nz/en/home/media/press-releases/2021/06/2021-kpmg-agribusiness-agenda.html. Accessed February 1, 2022.

Mattson. (2021). *Study on food Waste*. A confidential consultancy report prepared for the Upcycled Food Association.

Peschel, A. O., & Aschemann-Witzel, J. (2020). Sell more for less or less for more? The role of transparency in consumer response to upcycled food products. *J Clean Prod, 273*, 122884.

Prendergast, F. (2019). *Will New Zealand consumers accept the concept of upcycling surplus products from supermarkets?* BSc Honours Project, University of Otago, New Zealand.

Project Drawdown Solutions. (2020). Reduced food waste, https://drawdown.org/solutions/reduced-food-waste. Accessed February 1, 2022.

Sponshot. (2019). *Food trends: 9 biggest food trend predictions for 2022 & beyond*. https://sponshot.com/blog/food-trend-predictions-for-2022/. Accessed February 1, 2022.

Spratt, O., Suri, R., & Deutsch, J. (2021). Defining upcycled food products. *Journal of Culinary Science & Technology, 19*(6), 485–496.

Thorsen, M., Nyhof, F., Goodman-Smith, F., & Mirosa, M. (2021). Category managers' recommendations to manufacturers of upcycled food. http://hdl.handle.net/10523/12177

UNEP-United Nations Environment Programme. (2021). *Food Waste index report 2021*. Nairobi.

Waste 360. (2022). *Upcycled certified products projected to prevent 703 million pounds of food waste per year*. Press release January 13. https://www.waste360.com/food-waste/upcycled-certified-products-projected-prevent-703-million-pounds-food-waste-year?mc_cid=03e8990800&mc_eid=6f181855f9

WRAP - The Waste and Resources Action Programme. (2021). Food waste reduction roadmap. http://www.wrap.org.uk/content/why-take-action-legalpolicy-case. Accessed February 1, 2022.

WWF. (2021). Driven to Waste: Global Food Loss on Farms. https://www.worldwildlife.org/publications/driven-to-waste-the-globalimpact-of-food-loss-and-waste-on-farms

Zhang, J., Ye, H., Bhatt, S., Jeong, H., Deutsch, J., Ayaz, H., & Suri, R. (2021). Addressing food waste: how to position upcycled foods to different generations. *J Consum Behav, 20*(2), 242–250.

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12 Understanding New Foods: Development of Next Generation of Food Processing, Packaging, and Ingredients Technologies for Clean Label Foods

V. M. Balasubramaniam, James Lee, and Luca Serventi

Abstract

Modern consumers demand foods that are processed without synthetic additives and preservatives. The term "clean label" has been adopted to describe such food products. The global market for clean label products reached $180 billion in 2020. Reasons for this increased demand for clean label food products include health, environmental, and societal concerns. Consumers seem to be particularly skeptical of food ingredients used in processed foods that they do not know or ingredients they know as belonging to refined foods. Therefore, various technologies have been developed over the past decade, enabling the food processors to manufacture clean label food products. This includes high pressure-based food manufacturing technologies, active packaging, and natural antimicrobials, pigments, and other functional ingredients derived from plant and animal sources. Functionality as well as safety have been investigated to guarantee the technologies' applicability to the food industry. Sensory profile (appearance, aroma, taste, and texture) and shelf life both contribute to food quality. While some of natural ingredients have been demonstrated to be safe and efficient, others might be less effective. Opportunities for healthy, sustainable processing are viable, yet challenges do occur and should be addressed by current and future food scientists and engineers.

Keywords

Clean label · Emulsifiers · Food ingredients · Food manufacturing · High pressure · Packaging · Health and wellness

12.1 Introduction

Modern consumers demand "healthy" clean label processed foods that are free from synthetic additives and preservatives. Though health and wellness is a key driving factor, various socio-cultural, environmental, and scientific factors are also influenced the development of clean label products.

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(a) Food processors traditionally use a variety of synthetic additives for providing a range of useful functions in processed foods including maintaining safety, taste, texture, and appearance. In the era of social media, consumers are increasingly aware of numerous adverse effects of synthetic ingredients added in processed foods. Most of the consumers are confused by unfamiliar scientific names of ingredients and develop misconceptions about these ingredients in processed foods. Rather, they prefer to purchase processed foods containing all natural, easy to understand, familiar ingredients they may already use in their kitchen.
(b) Medical researchers began to highlight the adverse effects of processed foods on human health. For example, recent increases in obesity and various lifestyle diseases (Clark et al., 2019; Hruby & Hu, 2015) are linked with increased consumption of processed foods. Similarly, correlations between use of dietary emulsifiers (such as carboxymethylcellulose and polysorbate-80) in processed foods and increased incidence of chronic inflammatory disease through adverse effects on gut microbiome (Cani, 2015; Chassaing et al., 2022) have been reported.
(c) With increased interest in protecting the environment, consumers prefer processed foods that are manufactured using sustainable food processing technologies with reduced environmental impacts.
(d) The food industry, over the last three decades, adapted various novel thermal and nonthermal food manufacturing technologies, including high-pressure processing (Zhang et al., 2011). Food processors have industrially adapted such minimal processing technological solutions in order to reduce product thermal exposure and ensure microbiological safety of the product. Now the food processors begin to realize the potential of such technologies for manufacturing clean label products that satisfy consumer's desire for nutritious foods with fresh-like quality attributes and free from synthetic preservatives.

The global market share of clean label food products is estimated as $180 billion in 2020. Market share of clean label ingredients such as natural colors and flavors, starches and sweeteners, fruit and vegetable ingredients, flours, and others will increase from $38.8 billion in 2021 to $64.1 billion in 2026 (Brewster, 2021). The demand for clean-label foods continued to increase during COVID-19 pandemic, as consumers put emphasis on eating healthier meals during the pandemic.

While there is no formal legal definition for clean label foods, many food processors are proactively removing synthetic additives in their processed products to meet changing consumer expectations; examples include Kraft Foods (removal of artificial preservatives from macaroni and cheese), Nestle (removal of artificial flavors from frozen pizza), Whole Foods (banning artificial colors, flavors, and sweeteners in products sold in their stores), and Campbell Soup Company (removal of artificial flavors and colors). When removing or reducing the use of synthetic ingredients, attention must be paid to how such actions influence product safety, quality, and shelf life. This chapter summarizes how advanced food manufacturing, packaging, and ingredient technologies can help to shape future clean label food products.

12.2 Consumer Preference of Clean Label Products

Numerous market surveys have shown how consumers are looking for clean label food (Food & Beverage Insider, 2021; IFT, 2021). This broad term encompasses both ingredients and technologies. It typically involves avoiding additives and preservatives (Food & Beverage Insider, 2021). As many as two-thirds of US consumers have expressed interest in such foods. In fact, they actively read food labels and ingredients list to screen for unwanted ingredients and nutritional profile (IFT, 2021). The reasons behind this involve four key pillars (Fig. 12.1):

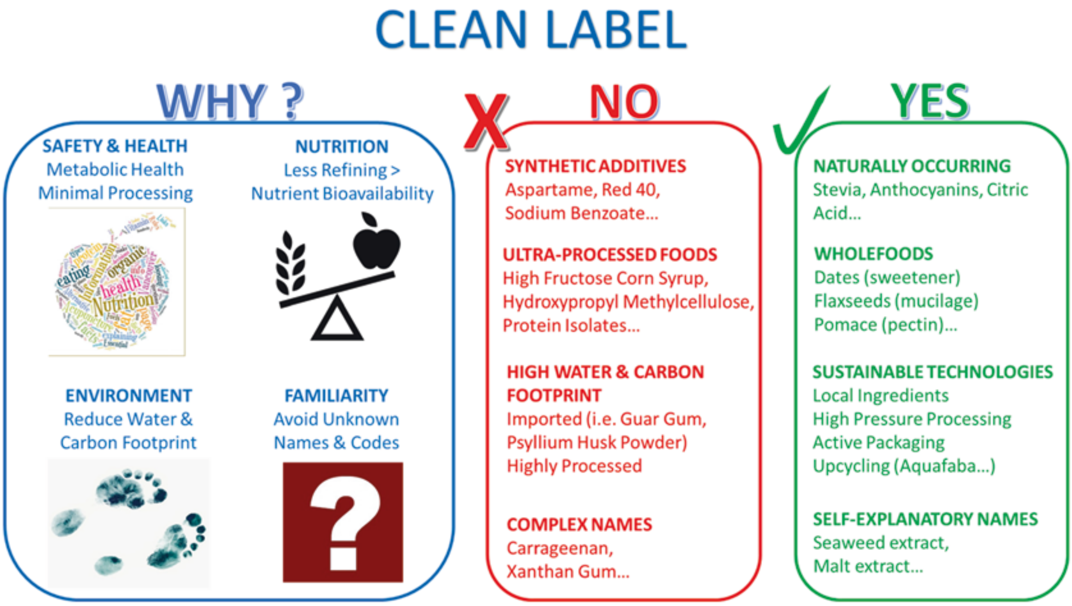

Fig. 12.1 Clean label foods concepts

– **Food safety and health** (metabolic health, minimal processing);
– **Nutrition** (highly refined ingredients cause nutrient loss and lower bioavailability);
– **Environment** (refining, extraction and import cause high water and carbon footprint);
– **Familiarity** (unknown names drive consumer away due to a lack of trust and need to understand).

In terms of safety and health, reports have highlighted the presence of common solvents in food additives (colors, dietary supplements, stabilizers, sweeteners). Specifically, the following compounds were found: ethanol, methanol, acetone, 2-propanol, ethyl acetate, and hexane. All these compounds were detected in quantities below the maximum limits set by local authorities (FDA in the USA, EFSA in the European Union and so on) (Uematsu et al., 2002; Uematsu et al., 2008). What sparked questions about safety and health impact of consuming processed foods was the impact of certain food additives. For examples, studies on the low calorie sweetener aspartame revealed cancer promoting activities due to methanol release upon its digestion. This was observed *in vitro* and in animal models (mice) (Maghiari et al., 2020; Soffritti et al., 2014). Due to a lack of human studies, caution has been promoted by some researchers, while green light has been given by others. Dosage and daily consumption also must be taken into account. This was made clear also by a study on a common texturizer (hydroxypropyl methylcellulose, HPMC) which was considered safe below daily doses of 5 mg/kg body weight (Burdock, 2007). Typical dosage of HPMC in food products (confectionery, dressing, gluten-free bread, ice cream and others) is about 0.1–5.0% of the food weight (Dourado et al., 2016; Encina-Zelada et al., 2019). Therefore, limited consumption is encouraged.

Nutrition-wise, some hydrocolloids may have beneficial effects due to their fiber content. Nonetheless, macronutrient isolation, such as protein, can cause losses of specific micronutrients, such as minerals and vitamins.

Environmentally, refining and processing cause increased uses of resources (water footprint) and greenhouse gas emissions (carbon footprint). In addition, popular additives (such as guar gum) are derived from plants that only grow in a few locations (Rajasthan, India). Import across the globe involves carbon emissions. Therefore, finding local alternatives will improve the sustainability of this food supply.

Finally, part of the clean label movement started off with a demand for transparency. Certain consumers do not recognize technical names and codes. They are not necessarily against the use of some ingredients, but rather demand clarification on their origin (raw material and processing).

Overall, a call for transparency outlined a demand for clear ingredient listing, using simple words as opposed to jargon or numerical codes. The food industry is responding by developing clean ingredients, especially in the areas of safety (mold inhibitors), taste (flavor) and texture (hydrocolloids) (IFT, 2021). Interestingly, a recent survey performed in 2021 outlined consumers' interest in labels with carbon footprints. This demand is supported by one of the reasons for clean label: environmental concerns (IFT, 2021).

While there have been numerous trade magazines reports documented increasing consumer preference towards clean label food products, very limited scientific literature is available in scholarly journals. A study on plant-based foods with free-from claims investigated the following products as case studies: gelatin-free candies, dairy-free ice cream, soy-free protein drinks, and meat-free sausages. Results highlighted three main categories of food ingredients: sweeteners, flavours and protein. Generally speaking, subjects identified most sweeteners as unhealthy, while their opinion on flavour and protein changed based on the ingredient origin and manufacturing. Unhealthy processing approaches (use of specific extraction solvents, extreme isolation of nutrients) and unfamiliarity with the ingredient name were identified as other reasons for rejection of processed foods (Aschemann-Witzel et al., 2019). Authors concluded that consumer education can prevent rejection soley due to unfamiliarity.

Maruyama et al. (2021) investigated how ingredient lists and associated sensory quality descriptions influence consumer preferences towards clean label food products. Authors conducted the experiments using 250 consumers in the USA by evaluating the impact of four stabilizers (carrageenan, corn starch, milk protein concentrate, and pectin) and textural characteristics on preferences and willingness to pay for plain yogurt. Results of the study suggests that while clean labeling increases consumer choice, poor texture reduces consumer choice. The adverse impact of poor texture appears to be less significant for clean label yogurts compared to that for yogurts with longer ingredient lists. Among all stabilizers, corn starch has a significant negative impact on consumer choice. While the price and quality are the important attributes for consumers, the study suggests that consumers have shown clear preference for clean labels, specifically, a minimal ingredient list. They may be willing to pay more for a clean label on plain (32-ounce) yogurt product. More scientific studies are necessary to understand consumer interest in clean label products on different food matrices.

Another USA study on yogurt revealed that perceived naturalness positively influenced the intent of purchase, whereas ingredient functionality (sweetener, emulsifier, thickener) did not affect it. Age also played a role with the younger generations declare to be more mindful of ingredient list. Specifically, a group of over 500 people was asked questions about the following yogurt ingredients: sweeteners, thickeners, preservatives and colorings. Within each of these four categories, significant differences were observed in terms of perceived naturalness. For example:

- Cane sugar was preferred over fructose as sweetener;
- Pectin was preferred over carrageenan and guar gum as thickener;
- Citric and lactic acids were preferred over sorbate as preservatives;
- Vegetable juice was preferred over carmine and Red 40 as coloring.

Results were not affected by functionality (sweetener, thickener, preservative, and coloring) but rather attributed to ingredient source, processing and familiarity. For example, the thickener carrageenan was considered significantly more natural after its origin (seaweed) was explained (Maruyama et al., 2021).

Experimental Survey

Consequently, a similar follow up study was conducted at Lincoln University, New Zealand. The survey was conducted among 26 science and commerce staff and students of the university. The survey consists of 3 paired questions to determine participant's views on clean label ingredients in yogurt. Survey questions employed ratings between 1 (not very likely) to 5 (very likely). Statistical significance was determined using a T-test. The first paired questions asked about participant's likelihood to accept pectin in yogurt, the second paired questions asked about participant's likelihood to accept lecithin in yogurt, and the third paired questions determined participant's likelihood to accept vitamin B12 in yogurt. Results are summarized in Table 12.1. The likelihood of participants accepting the use of pectin in yogurt increased after learning about how it is produced industrially. However, no statistically significant difference was observed, meaning that the likelihood of participants accepting pectin in food did not significantly increase after learning about industrial production: participants were 'neutral to likely' to accept pectin in yogurt.

Results from the emulsifier questions (lecithin) show that participants accepting lecithin in food increased significantly after learning about its industrial production. Finally, results from the nutritional supplement questions indicated that participants accepting the addition of vitamin B12 in yogurt was high, regardless of the explanations.

The general lack of statistically significant increases in acceptability of ingredients after learning about their industrial production may indicate that the participants do not view knowing about the ingredients in their food very highly. This may reflect a lack of interest in the clean label trend for yogurt products. However, a reason for this result may have been due to sample selection. Majority of the responses came from those in the science faculty. Therefore, the

Table 12.1 Statistical analysis of survey results

Question	Mean	*p-value*
Pectin		
Q1. How likely are you to accept a yoghurt that contains pectin?	3.46 ± 0.91	*0.304*
Q2. Pectin is a fibre found in the cell walls of most fruits. It is extracted using hot acid, diluted and dried Knowing this information, how likely are you to accept a yoghurt that contains pectin?	3.73 ± 0.96	
Lecithin		
Q3. How likely are you to accept a yoghurt that contains lecithin?	3.31 ± 0.74	*0.049*
Q4. Lecithin is a fat that can be commonly found in eggs, sunflowers, and soybeans. Commercially, lecithin is made by hydrating the seeds, filtering the mixture and drying Knowing this information, how likely are you to accept a yoghurt that contains lecithin?	3.73 ± 0.78	
Vitamin B12		
Q5. How likely are you to accept a yoghurt that is fortified with vitamin B12?	4.12 ± 0.99	*0.649*
Q6. Vitamin B12 is mainly found in meat, fish, eggs, and dairy. Supplements are produced through a fermentation process. Specific bacteria ferment a source of sugar. The vitamin B12 produced is then extracted using a solvent or resin and purified Knowing this information, how likely are you to accept a yoghurt that is fortified with vitamin B12?	4.23 ± 0.82	

participants would likely already have an understanding of these ingredients and their commercial applications, which would explain the lack of significant increase after learning about their industrial production. The scientific nature and small size of the sample (26 participants) mean that the results may not reflect the population well. Additionally, despite the lack of statistical significance, there is still a trend of increased acceptability of ingredients after their origins are explained, so clean label may still be a consideration for consumers.

Lecithin was the only ingredient which had a statistically significant increase in acceptability. This could have been due to lecithin not being as commonly known as the other two ingredients (pectin is used in home-cooking for making jams and vitamins are associated with health), so after learning how it is produced (in a fairly natural process), acceptability increased. Also, pectin and vitamin B12 are extracted using hot acid and resin or other solvents respectively, while lecithin is derived by soaking. Vitamin B12 fortification of yogurt had the highest average mean and participants were likely to accept it in yogurt. A reason for this could be that vitamins are nutrients which are known to provide health benefits. Therefore, consumers may be more willing to accept non-clean label ingredients as long as the health benefits of the food are clearly highlighted. More studies among consumers from different geographical regions are needed to understand consumer desire for clean label food in food product development.

Therefore, two approaches can be suggested: minimal processing and consumer education.

12.3 Technologies for Clean Label Foods

Successful introduction of clean label food products requires development of technologies for novel food processing, packaging, and ingredients.

12.3.1 Nonthermal Processing

Researchers have been investigating the application of various nonthermal lethal agents, such as high pressure, pulsed electric field, high-pressure homogenization, ozone, cold plasma, ultrasound, and ultraviolet light, to ensure microbial safety of foods (Balasubramaniam et al., 2016; NACMF, 2006; Zhang et al., 2011). These lethal agents can help food processors inactivate harmful vegetative bacteria and spoilage organisms commonly found in foods. While most of the nonthermal technologies investigated are effective in inactivating various vegetative bacteria, viruses, molds, and yeasts, spores mostly survive the treatment at ambient temperatures. Spores can be inactivated by combining nonthermal lethal agent with modest heat. In addition, nonthermal technologies have shown variable efficacy against inactivating enzymes. Among various nonthermal processes, high-pressure processing has been increasingly adapted by food processors as a technology that ensures food safety and development of clean label foods by reducing thermal exposure and improving product functionality.

12.3.2 High-Pressure Processing

High-pressure processing involves subjecting the pre-packaged food to high pressures (400–600 MPa) with or without external heat addition (Fig. 12.2). While pressure treatment at chilled or ambient temperatures produces pasteurized products, the combination of high pressure and heat (90–120 °C) is required to achieve commercial sterility (Balasubramaniam, 2021). High-pressure pasteurization has been industrially adapted by various food processors to process a variety of safe and nutritious foods without the need for synthetic chemicals. Meats, seafood, juices, sauces, and ready-to-eat meals are examples of value-added high-pressure pasteurized products. Though high-pressure processing was initially commercialized in 1997 in the USA as a

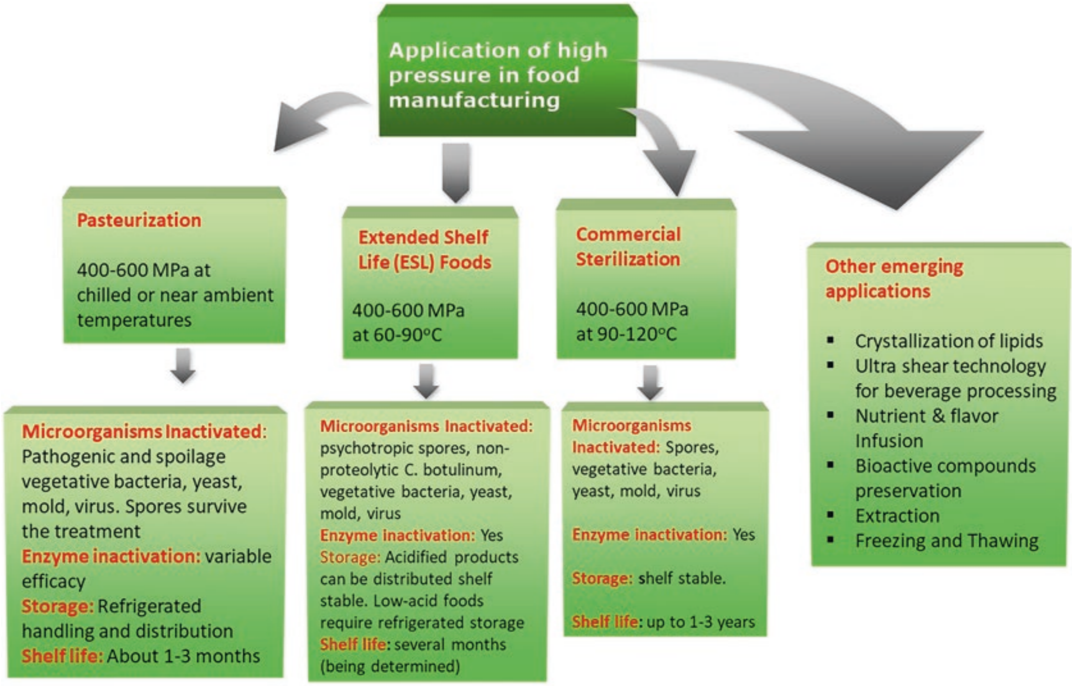

Fig. 12.2 Process development of high pressure-based technologies in food manufacturing

food safety technology, today the technology has been employed by food processors to satisfy consumer demand for clean label products by removing preservatives such as sodium benzoate, nitrites, and nitrates (Anon, 2018). Nitrites have been typically employed as a curing agent in meat products. High-pressure treatment of meats helped to remove such ingredients from treated products. Thus, high-pressure pasteurization facilitates the development of healthier clean label processed meats (Bolumar et al., 2021; Roobab et al., 2021).

Ultra-shear technology (UST), also known as high-pressure homogenization (HPH), is a semi-continuous method of pressure treating liquid foods. During the process, the liquid beverage is pressurized to target pressure and discharged via a shear valve at the target temperature. During passage through the shear valve, the pressure energy is converted into kinetic energy, generating heat, shear force, cavitation, and turbulence (Martínez-Monteagudo et al., 2017). Due to the conversion of pressure energy into kinetic energy, UST could modify food properties by reducing particle size, altering rheological characteristics, and modifying protein structures. This modification may help to produce various clean label beverages, including nutritional protein drinks, sauces, food emulsions, and liquid foods (Janahar et al., 2021). No UST-treated beverages are commercially available as of now. Belmiro et al. (2022) evaluated the feasibility of high-pressure homogenized coffee by-products as potential healthy clean label ingredients for making cookies. Incorporation of coffee by-products increased fiber content and total reducing power in the cookies without causing major changes in physical or sensory attributes of the product. Martínez-Monteagudo et al. (2017) concluded that the treatment may also help reduce synthetic stabilizer concentration in dairy beverages.

12.4 Packaging Technologies for Clean Label Products

Food packaging material selection is also a critical component of manufacturing clean label foods. Packages help the food processors to communicate and highlight some of the claims on clean label products so that consumers can make informed purchasing decisions. The package should also be free from any harmful additives. For example, with increased consumer sensitivity, food processors now prefer to utilize BPA-free packaging materials.

Since clean label products do not use synthetic preservatives, additives, and stabilizers, active packaging can be utilized by the food processors to protect the product. Active packages make use of various active ingredients and components (such as scavengers for oxygen and ethylene, carbon dioxide absorbers and emitters, time-temperature indicators, radio-frequency trackers, antimicrobial agents, and antioxidants) in the package for preserving and enhancing product quality and shelf life (Singh et al., 2021; Janjarasskul & Suppakul, 2018). Such ingredients may be placed inside the package via sachets or pads or incorporated into the packaging to perform certain functions (e.g., antimicrobial or antioxidant functions) beyond protection of the product. For example, clean label snack foods free from synthetic additives, including butylated hydroxyanisole, butylated hydroxytoluene, tertiary butylhydroquinone, and trans fats, require protection from lipid oxidation.

High barrier active packaging material with gas flushing, temperature controls, and oxygen absorbers may reduce oxygen exposure in meats, cereals, and dried fruits (Sand, 2017). Natural antimicrobial compounds incorporated into packaging materials may be useful for delaying or preventing growth of pathogenic and spoilage microorganisms. An example is the use of sachets containing eugenol, carvacrol, and trans-anethole, compounds with known antimicrobial activities, which allow preservation of organic ready-to-eat iceberg lettuce (Wieczyńska et al., 2016). Finally, most of the current food packaging are made from polymers that are noncompostable and difficult to degrade. For example, in the USA alone, food and packaging materials contribute about 45% of the materials landfilled and have major environmental impact. Future research efforts should focus on the development of biodegradable food packaging material as well as approaches for recycling packaging material for reducing packaging waste.

12.5 Natural Ingredients for Clean Label Products

Processed foods are formulated and stabilized with a variety of ingredients, including colorants, flavor agents, emulsifiers, antimicrobial agents, and agents for modifying rheological characteristics. With the growth of clean label foods, the demand for natural clean label ingredients is increasing. For example, in the United States, the clean label ingredients market was valued at $38.8 billion in 2018 and is forecasted to reach $64.1 billion by 2026.

Development of clean label products requires in part reducing or eliminating the use of various synthetic ingredients from natural sources. Such natural additives include various natural antimicrobial agents, natural antioxidants, carotenoids, and essential oils (Carocho et al., 2014). Extracts from cinnamon, rosemary, thyme, oregano, and similar essential oils, as well as chitosan are used as natural antimicrobial agents.

Traditionally, antimicrobial ingredients are added to formulated foods to provide bacteriostatic effects during extended storage. In addition, it is possible to combine natural ingredients with various nonthermal technologies synergistically to reduce process severity. For example, researchers have demonstrated that natural antimicrobial compounds such as essential oils can be synergistically combined with high-pressure processing to reduce process severity (Chuang & Sheen, 2022; Daryaei et al., 2016; Evrendilek & Balasubramaniam, 2011). Raghubeer et al. (2020) reported that various strains of *C. botulinum* spores inoculated in raw, pressure-pasteurized coconut water did not grow or produce toxins when stored for 45 days at 4 °C and 10 °C. The authors attributed this lack of growth to the presence of natural antimicrobial compounds such as lauric acids, antimicrobial peptides, and other substances present in coconut water. Such compounds inhibit growth and toxin production of non-proteolytic and proteolytic strains of *C. botulinum* when stored at ≤10 °C. More research is needed to evaluate the synergy between various natural antimicrobial agents in combination with different processing and packaging technologies.

While nonthermal technology treatment may help to formulate clean label products by reducing or removing additives (such as nitrites and sulfites from high-pressure pasteurized meat products), potential adverse effects of reducing or removing these additives on product safety, quality, and shelf life need to be considered as a part of process development of clean label products. For example, in conventionally treated products, nitrites also contribute to the development of the color and flavor of cured meat products. The reduction or removal of antioxidants may promote higher levels of oxidation. Such effects must be considered before changes to the product formulation are made.

Synthetic compounds have well-defined molecules with low batch-to-batch variability. On the other hand, natural ingredients often lack the process and storage stability of synthetic ingredients. It is important for natural ingredients to deliver their function in formulated foods without adversely impacting organoleptic properties of foods. For example, while various plant-based essential oils have demonstrated antimicrobial activities, such compounds may introduce distinct flavors in the formulated products that may not be appreciated by the consumers. In addition, such compounds may have water solubility and stability. Some of the protein-based natural antimicrobial compounds may lose antimicrobial properties when treated under different nonthermal technologies. Various pigments associated with natural colorant sources (e.g., anthocyanins, betalains, carotenoids) may be degraded under certain heat, acidic, and light conditions during processing and extended storage (Weber & Larsen, 2017). Research is underway to modify natural ingredients by nanoencapsulation or similar approaches to improve their stability while retaining functionality.

12.6 Limitations to Consider When Developing Clean Label Processed Foods

It is important to realize that clean label processed food by itself may not assure the processed product is a healthier choice for consumers. The product may still contain elevated levels of sugar, salt, and fat, which may not be desired by the consumer. Food processors motivated to develop consumer-desired clean label products may ignore the need to fortify processed foods with vitamins and minerals, many of which have “chemical-sounding” names (Shelke, 2020). Raw foods may be contaminated with mercury, zinc, arsenic, and lead from soil, chemical fertilizers, and pesticides. Similarly, fish may be contaminated with mercury from sea or river water. While many of the conventional and novel food processing methods are effective in microbial safety and preserve product quality, limited studies investigated the technologies' effectiveness against some of these chemical contaminants, which may lead to adverse health effects. More research is needed to develop processing and/or ingredient-based intervention strategies for eliminating these contaminants. Finally, in the era of social media, consumers are mostly presented with adverse effects of processed foods while overlooking many positive benefits of various synthetic ingredients in processed foods. The food science and engineering community needs to engage with consumers to highlight the positive benefits of food processing, packaging, and various ingredients in food preservation.

12.7 Conclusions

Development of the next generation of clean label foods requires coordinated efforts and communication among various stakeholders including academia, food processors, retailers, policy makers, and consumers. Development of clean label products cannot be realized by simple removal of preservatives or synthetic ingredients. Multidisciplinary research and development efforts in various processes, packaging, and ingredient technologies are critical. Development of these clean label foods requires careful product reformulation and changes in the food manufacturing and filling processes.

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References

Anonymous. (2018). Questions and answers: High pressure processing with Universal Pure's Mark Fleck. *Food Manufacturing*. August 15, 2018.

Aschemann-Witzel, J., Varela, P., & Peschel, A. O. (2019). Consumers' categorization of food ingredients: Do consumers perceive them as 'clean label' producers expect? An exploration with projective mapping. *Food Quality and Preference, 71*, 117–128.

Balasubramaniam, V. M. (2021). Process development of high pressure-based technologies for food: Research advances and future perspectives. *Current Opinion in Food Science, 42*, 270–277C. https://doi.org/10.1016/j.cofs.2021.10.001

Balasubramaniam, V. M., Barbosa-Cánovas, G. V., & Lelieveld, H. (2016). In *High pressure processing of food: Principles, technology and applications (food engineering series)* (1st ed.). Springer. https://doi.org/10.1007/978-1-4939-3234-4

Belmiro, R. H., Oliveira, L. D. C., Tribst, A. A. L., & Cristianini, M. (2022). Techno-functional properties of coffee by-products are modified by dynamic high pressure: A case study of clean label ingredient in cookies. *LWT, 154*(15), 112601.

Bolumar, T., Orlien, V., Sikes, A., Aganovic, K., Bak, K. H., Guyon, C., Stübler, A.-S., de Lamballerie, M., Hertel, C., & Brüggemann, D. A. (2021). High-pressure processing of meat: Molecular impacts and industrial applications. *Comprehensive Reviews in Food Science and Food Safety, 20*, 332–336. https://doi.org/10.1111/1541-4337.12670

Brewster E (2021) The changing face of clean label. Food Technology. September 2021.

Burdock, G. A. (2007). Safety assessment of hydroxypropyl methylcellulose as a food ingredient. *Food and Chemical Toxicology, 45*(12), 2341–2351.

Cani, P. D. (2015). Metabolism: Dietary emulsifiers – sweepers of the gut lining? *Nature Reviews. Endocrinology, 11*(6), 319–320.

Carocho, M., Barreiro, M. F., Morales, P., & Ferreira, I. C. F. R. (2014). Adding molecules to food, pros and cons: A review on synthetic and natural food additives. *Comprehensive Reviews in Food Science and Food Safety, 13*, 377–399. https://doi.org/10.1111/1541-4337.12065

Chassaing, B., Compher, C., Bonhomme, B., Liu, Q., Tian, Y., Walters, W., Nessel, L., Delaroque, C., Hao, F., Gershuni, V., Chau, L., Ni, J., Bewtra, M., Albenberg, L., Bretin, A., McKeever, L., Ley, R. E., Patterson, A. D., Wu, G. D., Gewirtz, A. T., & Lewis, J. D. (2022). Randomized controlled-feeding study of dietary emulsifier Carboxymethylcellulose reveals detrimental impacts on the gut microbiota and metabolome. *Gastroenterology, 162*(3), 743–754. https://doi.org/10.1053/j.gastro.2021.11.006

Chuang, S., & Sheen, S. (2022). High pressure processing of raw meat with essential oils-microbial survival, meat quality, and models: A review. *Food Control, 132*, 108529. https://doi.org/10.1016/j.foodcont.2021.108529

Clark, M. A., Springmann, M., Hill, J., & Tilman, D. (2019). Multiple health and environmental impacts of foods. *Proceedings of the National Academy of Sciences of the United States of America, 116*(46), 23357–23362. https://doi.org/10.1073/pnas.1906908116

Daryaei, H., Balasubramaniam, V. M., Yousef, A. E., Legan, J. D., & Tay, A. (2016). Lethality enhancement of pressure-assisted thermal processing against *bacillus amyloliquefaciens* spores in low-acid media using antimicrobial compounds. *Food Control, 59*, 234–242. https://doi.org/10.1016/j.foodcont.2015.05.029

Dourado, F., Leal, M., Martins, D., Fontão, A., Rodrigues, A. C., & Gama, M. (2016). Celluloses as food ingredients/additives: Is there a room for BNC? In *Bacterial nanocellulose* (pp. 123–133). Elsevier.

Encina-Zelada, C. R., Cadavez, V., Teixeira, J. A., & Gonzales-Barron, U. (2019). Optimization of quality properties of gluten-free bread by a mixture design of xanthan, guar, and hydroxypropyl methyl cellulose gums. *Food, 8*(5), 156.

Evrendilek, G. A., & Balasubramaniam, V. M. (2011). Inactivation of listeria monocytogenes and *listeria innocua* in yogurt drink applying combination of high-pressure processing and mint essential oils. *Food Control, 22*(8), 1435–1441. https://doi.org/10.1016/j.foodcont.2011.03.005

Food & Beverage Insider. (2021). Consumers will pay premium for clean label. URL: https://www.foodbeverageinsider.com/market-trends-analysis/consumers-will-pay-premium-clean-label. Accessed on April 13, 2022.

Hruby, A., & Hu, F. B. (2015). The epidemiology of obesity: A big picture. *PharmacoEconomics, 33*(7), 673–689. https://doi.org/10.1007/s40273-014-0243

IFT. (2021). The changing face of clean label. URL: https://www.ift.org/news-and-publications/food-technology-magazine/issues/2021/september/columns/ingredients-clean-label. Accessed on April 13, 2022.

Janahar, J. J., Marciniak, A., Balasubramaniam, V. M., Jimenez-Flores, R., & Ting, E. (2021). Effects of pressure, shear, temperature and their interactions on milk selected quality attributes. *Journal of Dairy Science, 104*(2), 1531–1547.

Janjarasskul, T., & Suppakul, P. (2018). Active and intelligent packaging: The indication of quality and safety. *Critical Reviews in Food Science and Nutrition, 58*(5), 808–831. https://doi.org/10.1080/10408398.2016.1225278

Maghiari, A. L., Coricovac, D., Pinzaru, I. A., Macaşoi, I. G., Marcovici, I., Simu, S., et al. (2020). High concentrations of aspartame induce pro-angiogenic effects in ovo and cytotoxic effects in HT-29 human colorectal carcinoma cells. *Nutrients, 12*(12), 3600.

Martínez-Monteagudo, S. I., Kamat, S., Patel, N., Konuklar, G., Rangavajla, N., & Balasubramaniam, V. M. (2017). Improvements in emulsion stability of dairy beverages treated by high pressure homogenization: A pilot-scale feasibility study. *Journal of Food Engineering, 193*, 42–52. https://doi.org/10.1016/j.jfoodeng.2016.08.011

Maruyama, S., Lim, J., & Streletskaya, N. A. (2021). Clean label trade-offs: A case study of plain Yogurt. *Frontiers in Nutrition*. https://doi.org/10.3389/fnut.2021.704473

Maruyama, S., Streletskaya, N. A., & Lim, J. (2021). Clean label: Why this ingredient but not that one? *Food Quality and Preference, 87*, 104062.

National Advisory Committee on Microbiological Criteria for Foods. (2006). Requisite scientific parameters for establishing the equivalence of alternative methods of pasteurization. *Journal of Food Protection, 69*(5), 1190–1216.

Raghubeer, E. V., Phan, B. N., Onuoha, E., Diggins, S., Aguilar, V., Swanson, S., & Lee, A. (2020). The use of high-pressure processing (HPP) to improve the safety and quality of raw coconut (*Cocos nucifera L*) water. *International Journal of Food Microbiology, 331*, 108697.

Roobab, U., Khan, A. W., Lorenzo, J. M., Arshad, R. N., Chen, B.-R., Zeng, X.-A., Bekhit, A. E.-D. A., Suleman, R., & Aadil, R. M. (2021). A systematic review of clean-label alternatives to synthetic additives in raw and processed meat with a special emphasis on high-pressure processing (2018–2021). *Food Research International, 150*, 110792. https://doi.org/10.1016/j.foodres.2021.110792

Sand, C. K. (2017). Packaging solutions for clean label products. *Food Technology 71*. January 2017.

Shelke, K. (2020). Clearing up clean label confusion. *Food Technology*. February 1, 2020.

Singh, A. K., Ramakanth, D., Kumar, A., Lee, Y. S., & Gaikwad, K. K. (2021). Active packaging technologies for clean label food products: a review. *Journal of Food Measurement and Characterization, 15*, 4314–4324. https://doi.org/10.1007/s11694-021-01024-3

Soffritti, M., Padovani, M., Tibaldi, E., Falcioni, L., Manservisi, F., & Belpoggi, F. (2014). The carcinogenic effects of aspartame: The urgent need for regulatory re-evaluation. *American Journal of Industrial Medicine, 57*(4), 383–397.

Uematsu, Y., Hirata, K., Suzuki, K., Iida, K., & Kamata, K. (2002). Survey of residual solvents in natural food additives by standard addition head-space GC. *Food Additives & Contaminants, 19*(4), 335–342.

Uematsu, Y., Ogimoto, M., Suzuki, K., Kabashima, J., Ito, K., & Nakazato, M. (2008). Survey of residue levels of organic solvents in "existing food additives" and health food materials by head-space GC. *Shokuhin Eiseigaku Zasshi/Journal of the Food Hygienic Society of Japan, 49*, 366–375.

Weber, F., & Larsen, L. R. (2017). Influence of fruit juice processing on anthocyanin stability. *Food Research International, 100*(3), 354–365. https://doi.org/10.1016/j.foodres.2017.06.033

Wieczyńska, J., Luca, A., Kidmose, U., Cavoski, I., & Edelenbos, M. (2016). The use of antimicrobial sachets in the packaging of organic wild rocket: Impact on microorganisms and sensory quality. *Postharvest Biology and Technology, 121*, 126–134.

Zhang, H. Q., Barbosa-Cánovas, G. V., Balasubramaniam, V. M., Dunne, C. P., Farkas, D. F., & Yuan, J. T. C. (2011). *Nonthermal processing technologies for food*. Wiley Blackwell Publishers. https://doi.org/10.1002/9780470958360

13 Understanding New Foods: Water Quality

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Abstract

Water scarcity and water pollution are in hot debate in society, and water reuse has become an important measure of the water conservation plan. It is important to understand consumers' perceptions of the environment, water quality, and food wastewater reuse. Food wastewater reuse is a promising method of reclaiming wastewater. For example, by-products such as acid whey and tofu whey can be used to manufacture new products. This report aims to assess consumers' perceptions of water quality and acceptance of new whey beverages in 26 provinces in China. Data are collected by referring to peer-reviewed literature, related websites, social network sites, and other platforms, and formulating a questionnaire survey of 18 questions (n = 130). The results show that consumers have a certain degree of concern about the water quality of their living environment and worry about the safety of reclaimed water. Food safety is a priority for consumers when buying new whey products. Curiosity, environmental awareness, and the price will also affect their purchase intention. The research and development on the food application of acid whey and tofu whey are still in progress, and converting them into functional beverages is the main innovation direction of researchers. Reducing consumers' risk perception of these two whey types will help increase their acceptance.

Keywords

Water reuse · Circular economy · Consumer · Purchase intention · Acid whey · Tofu whey

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13.1 Introduction

Water is not only an important material for maintaining a healthy ecosystem, but also an indispensable resource for social and economic development. Due to the acceleration of industrial construction, economic development, and

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urbanization, water consumption continues to increase (Meneses et al., 2017). It is estimated that by 2040, global water consumption will reach 4.35 trillion cubic meters (Tiseo, 2019). The water footprint represents the number of freshwater resources consumed to produce a certain product or provide a certain service (Hogeboom, 2020). Agriculture is one of the industries that consumes the most water in the world, especially in irrigation. For example, in China, agricultural water consumption accounts for 70% of the total water consumption (Winpenny et al., 2010). Crops have a higher water footprint, but animal-derived foods generally have greater water footprints than plant-derived foods (Mekonnen & Hoekstra, 2012). Human living standards have gradually improved, and more and more people's dietary choices have turned to high protein foods, some of which have led to an increase in water demand, resulting in water scarcity (González et al., 2020). For example, production of 1 liter of milk requires approximately 5,000 liters of water (Mekonnen & Hoekstra, 2011). A common alternative to milk, that is considered more sustainable by many, is almond milk. Nonetheless, almond production requires much more water, as high as 13,000 L of water per kg almonds (Vanham et al., 2020) while almond milk only delivers low quantities of nutrients due almonds limited solubility in water. Nutrient density and protein content must be factored in when comparing the environmental impact of food industries. When doing so, almonds require the least water per protein, closely followed by milk: 65 vs. 145 L water/g protein for almond and milk, respectively. This estimate is greatly outweighed by almond milk: 3,270 L water/g protein, which is 50 times higher than the value recorded for almonds (Mekonnen & Hoekstra, 2011; NZ Food Data Composition, 2021; USDA, 2021; Vanham et al., 2020).

In addition, in food processing industries, water participates in many food processing unit operations, which produce large amounts of wastewater that pose harm to the environment (Casani et al., 2005). The problems of water scarcity and environmental pollution have seriously affected the living environment and economic development, restricted the development of agriculture, and endangered food security and public health. These issues are a source of heated discussion among global lawmakers as well as the public.

In order to solve or alleviate the global water scarcity situation, many countries are working on improving the water utilization rate in terms of irrigation and reclaimed water, and they research and promote actively various water conservation technologies (Casani et al., 2005). Food Codes (Code of Federal Regulation CFR and Codex) stated that wastewater must be treated in a hygienic manner that does not contaminate food or food equipment (FDA, 2017). At present, the food processing industry has taken relevant measures to treat food wastewater, including membrane filtration technology (such as ultrafiltration, nanofiltration, reverse osmosis), biological treatment technology, Membrane Bioreactor (MBR), and others (Meneses et al., 2019). In addition, an effective way to save water is to recycle wastewater and make it into edible products. The annual output of wastewater from the food industry is large. Wastewater such as acid whey and tofu whey, which are by-products of the production of Greek yogurt (Lindsay et al., 2018) and tofu (Chua & Liu, 2019), respectively, both have high nutritional value. However, they contain high levels of biological oxygen demand (BOD) and chemical oxygen demand (COD), which in some cases is up to 10 g/L (Cassano et al., 2015). These high BOD and COD cause environmental issues if the wastewater is discharged. Specifically, high levels of these indicators can cause eutrophication: excessive concentration of nitrogen and phosphorous in freshwater. The result is a lack of oxygen for native species (such as fish) resulting in altered ecosystems, with fish death and production of toxins (Khan & Mohammad, 2014). Hence, using them to make new products is a sustainable solution that can reduce water eutrophication and water pollution caused by discharge into rivers.

Currently, there are no products derived from acid whey and tofu whey, and there is also a lack of consumer perception of them and no evaluation of the potential acceptance of their products. Therefore, the purpose of this study is to investigate consumers' perceptions of water quality and the discussion of these two types of whey as sources of new products. Conducting this research generates justification to improve research and promotion of such new products since it aims to collect and judge consumers' attitudes toward the recycling of food wastewater.

13.2 Consumer Discussion on Social Media

13.2.1 Data Collection

13.2.1.1 Peer-Reviewed References and Websites

The main websites include ScienceDirect, Lincoln Library, Google Scholar, and so on. The data were searched in terms of water conservation, water management, reclaimed water, water shortage, wastewater treatment, acid whey, tofu whey, risk perception, etc. The nutrition and food applications of acid whey and tofu whey as examples in this report will be mentioned. Moreover, the papers found will be compared with the results of the questionnaire survey to confirm their correctness or incorrectness.

13.2.1.2 Social Network Site and Forums

Social network sites mainly include Facebook, Twitter, Instagram, and Zhihu (a Q&A community in China). In view of the fact that acid whey and tofu whey are a new type of food raw materials, people talk less about them on social network sites and forums. Therefore, consumers' views and perceptions of water quality are the key data for the main search. In addition, people's attention to local water quality, wastewater treatment methods, and sources of water pollution will be discussed. These data will be used to create word clouds through the WordArt website, and will be compared with the results of the survey.

13.2.1.3 Consumers' Survey on Their Views Toward the Reconditioning and Reuse of Wastewater from Food Processing

The questionnaire survey collected data from 26 provinces in China through Sojump (an online survey tool). There were a total of 130 respondents, of which 93 were female and 37 were male. The age of the respondents ranged from 18 to 60, and most of them were 18–25 years old. The educational background includes high school, technical secondary school, junior college, bachelor's degree, master's degree and above, most of which have a bachelor's degree. The professional positions of the respondents include students, government officials, ordinary office clerk, professionals, etc. The specific demographic information is shown in Table 13.1 (Q1–Q5).

Using survey data on consumers' views of water reconditioning and reuse, we first assessed people's attitudes and perceptions of the living environment, water treatment, and wastewater sources, which came from Q6 to Q11. Questions 12 to 18 investigated consumers' acceptance of new products made from acid whey and tofu whey, mainly reflecting in terms of their perceptions of the two whey, curiosity of the products, environmental awareness, price, and food safety. The design of the questionnaire refers to the survey method of Adams et al. (2013). A questionnaire is deemed invalid if any one item is missing in the basic information column of the survey object or if two or more other questions are not answered. In the end, 130 valid questionnaires were obtained. The survey results are shown in Table 13.2.

In the survey, questions about consumers'perception of water quality and water treatment include: (1) Do you often pay attention to local water quality? (2) Do you think the current water pollution is serious? (3) The main sources of water pollution (e.g., industrial production wastewater, domestic sewage, agricultural wastewater); (4) The impact of untreated food industry wastewater on the environment; (5) Food industry wastewater treatment methods; (6) Acceptance of the

Table 13.1 Demographics of survey respondents (n = 130)

	Respondents (%)
Gender	
Male	28.5
Female	71.5
Age	
18-25	67
26-30	16
31-40	7.0
41-50	4.0
50-60	6.0
Educational background	
High school	3.0
Technical secondary school	6.0
Junior college/ Bachelor degree	77
Master degree and above	8.0
Position	
Student	60
Government officials	4.0
Ordinary office clerk	13
Professionals (e.g. teacher, doctor, etc.)	11
Others	12

Table 13.2 Statistical analysis of questionnaire survey (n = 130)

Description	Results
Degree of concern for local water quality (1-Never, … 5- Always)	3.41 ± 0.98
The main sources of water pollution industrial wastewater (1-yes, 0-no) domestic sewage (1-yes, 0-no) agricultural sewage (1-yes, 0-no) others (1-yes, 0-no)	0.90 ± 0.30 0.87 ± 0.34 0.47 ±0.50 0.02 ± 0.15
Degree of understanding of wastewater treatment (1- don't know, … 5- know well)	2.58 ±1.00
Acceptance of water reconditioning and reuse (1- low acceptance, … 5- high acceptance)	3.3 ± 1.13
Food safety consideration of food industry wastewater (1- not worried, … 5- very worried)	3.86 ± 0.94
Degree of understanding of tofu whey (1- yes, 0- no)	0.50 ± 0.50
Degree of understanding of acid whey (1- yes, 0- no)	0.24 ± 0.46
Buying products made from acid whey or tofu whey due to curiosity (1- unwilling, … 5- very willing)	3.13 ± 0.79
Buying the products due to environmental awareness (1- unwilling, … 5- very willing)	3.31± 0.85
Buying the products due to low price (1- unwilling, … 5- very willing)	3.53 ± 0.86
Buying the products due to guaranteed food safety (1- unwilling, … 5- very willing)	3.99 ± 0.89

recycling of wastewater from the food industry. Moreover, questions about consumer acceptance of products made from acid whey or tofu whey include: (1) The hygiene and safety of products made from food industry wastewater; (2) Understanding of acid whey and tofu whey; (3) Purchase intention of the new products.

13.2.1.4 Data Analysis by Word Clouds

All data were searched based on the purpose of this research report. Making word clouds can combine the relevant discussions of water quality, acid whey and tofu whey, and highlight the key points. Referring to Adams et al. (2013), the results of this questionnaire survey are listed using quantifiable single-choice or multiple-choice options (the scale is 1–5 or 0–1), and they were quantitatively analyzed. In order to conform to cognition and facilitate comparison, the questionnaire scores are finally converted into averages and percentages. The risk perception of consumers was evaluated by comparing the knowledge, attitudes, and behaviour of consumers on water reconditioning and reuse.

13.2.2 Discussion of Consumers' Perception

13.2.2.1 Perception of Water Quality

The problem of water pollution and water scarcity has always been a frequently debated topic in modern society. It will continue to be a permanent topic in the world, since it is related to human health and development (Fig. 13.1). People's perception of water resources affects their water use concepts and behaviour (Lease et al., 2014). Their awareness of water quality issues is the first research field of this investigation. The questions and corresponding results of the questionnaire survey are summarized in Table 13.2.

When respondents were asked how often they are concerned about the water quality of their living environment, with a scale of 1–5 to determine the data, most people will sometimes pay attention to water quality issues (mean 3.41). This mean also shows that they have a certain degree of attention to water and environmental issues. The results of the study by Eck et al. (2019) are similar to this data, but more respondents are paying

Fig. 13.1 Word clouds from social discussion on water quality, acid whey, and tofu whey

attention to the water situation. It shows that most of the general public, water professionals, and professional students in Oklahoma State are concerned about clean water (Eck et al., 2019). The reason for the higher attention is likely to be the difference in the region, the water quality, and the deeper understanding of water (Moosavi et al., 2021). When asked to choose the main source of water pollution among industrial wastewater, domestic sewage, agricultural wastewater, and other pollution sources (1 = yes, 0 = no), most questionnaire respondents chose the first two (mean value 0.9 and 0.87, respectively), about half of the people chose agricultural wastewater (0.47), and a very small number of them chose other pollution sources (0.02) but did not specify the source. According to UNESCO (2016), global industries discharge 30–40 billion tons of wastewater into water bodies every year, which also reveals that industrial wastewater is putting increasing pressure on the implementation of measures to protect water bodies. It is reported that agricultural water consumption accounts for 70% of total water consumption, and the amount of sewage produced is also harmful to the environment (Winpenny et al., 2010). More and more people believe that inorganic substances (such as nitrogen, phosphorus, cadmium, etc.) and organic substances (such as pesticide residues) contained in domestic sewage and agricultural wastewater pose great threats to the ecosystem, which greatly increases the total pollutant load (Xie et al., 2007). Based on statistics, Asia's annual wastewater volume is as high as 160 million cubic meters, while North America and Europe produce approximately 67 billion cubic meters each year (Tiseo, 2020). Hence, people have a great responsibility for the treatment of wastewater.

The composition of wastewater from food processing plants is relatively complex, including production processes such as sugar making, brewing, meat, and dairy processing, which all contain organic matter with a strong aerobic property, and a large amount of suspended matter is discharged with the wastewater (Cassano et al., 2015). When the respondents were asked whether the direct discharge of untreated food industry wastewater into water bodies or other places would affect the environment, 89.6% of them thought the impact was greater, and only 2.22% of them disagreed with this point of view, which reflects the importance of wastewater treatment. The survey by Petrescu et al. (2019) also shows that consumers agree that untreated wastewater has a highly negative impact on the environment and human health, which is consistent with the results of this survey. It is reported that food industry wastewater is a biodegradable water resource and does not contain toxic chemicals, but it has significant BOD and COD values, which can increase the pollution level of water resources if without wastewater treatments (Meneses et al., 2019). In the Food Code, the FDA (2017) requires food processing plants to treat wastewater in a wastewater treatment plant before discharging the wastewater into the water body, so as to meet the dischargeable wastewater standards. On average, most consumers do not know much about wastewater treatment methods in food factories (mean response of 2.58, on a 1–5 knowledge scale) (Table 13.2). Consumers seem to care more about the cleanliness and safety of water than wastewater treatment or water management.

13.2.2.2 Acceptance of Whey Products

Acid whey and tofu whey are recycled by food factories or laboratories because of their valuable nutrients to make new whey products, so as to realize the valorization of these two kinds of food wastewater (Chua & Liu, 2019). Consumers' willingness to buy new products often depends on their knowledge of the product's raw materials, processing methods, product innovation, price, and product safety. Therefore, the purchase intention of consumers is mainly collected through questionnaire surveys (Table 13.2).

When consumers were asked about their acceptance of water reconditioning and reuse, with a scale of 1–5 to test, and the result was that most people chose the median value (3.3). It is obvious that their acceptance of reclaimed water was at a general level, but there were still some consumers who fully accept this recycling measure. The main reason is reflected in the next question of the survey, "Are you worried about the hygiene and safety of products made from food industry wastewater?" Most consumers are worried about the kind of product (3.86). Consumers lack the perception of wastewater reuse, which will increase their negative attitudes towards reclaimed water. Lease et al. (2014) found that consumers' responses become positive when they obtain trustworthy information, and they generally accept or try to accept reclaimed water. Tofu whey and acid whey were previously considered to be of little value by the food industry, but now as a new type of food raw material, it can reduce the burden on wastewater discharge (Wang & Serventi, 2019). However, consumers also have little knowledge of tofu whey and acid whey. It is investigated that on the scale of 0–1, half of the consumers know about tofu whey, but most people pour it away directly. In contrast, people know less about acid whey, with an average value of 0.24. The reason may be different regional diets. Greek yogurt is very popular in the United States, and its production is increasing year by year (USDA, 2021), hence, consumers also have a certain understanding of acid whey. Some content about consumers cooking acid whey or tofu whey into new foods can be found on social network sites such as Twitter and Facebook, and the food applications of these two types of whey will be shown later. These two sources of whey as well as other types have been mentioned in the questionnaire for follow-up investigation.

The survey investigated consumer attitudes and behaviour toward whey products in terms of curiosity, environmental awareness, price, and food safety issues. It can be found from Table 13.2 that the average score in all aspects is 3–4. A study believes that new products can attract consumers' attention, stimulate their curiosity, and generate an urge to approach the product (Gerrath & Biraglia, 2021). However, the survey showed that respondents were hesitant to such products (mean 3.13). Curiosity cannot increase their purchasing desire, which reflects consumers' neophobia. Neophobia is defined as a resistive response to a food that people have never eaten before, and it is an inadaptability to new things (Nezlek et al., 2021). Uncertainty about the reliability of whey wastewater reuse technology makes consumers fear new products, and this phenomenon exists in both developing and developed countries (Coppola & Verneau, 2018). When asked whether they would include environmental awareness in their decision to accept these whey products, respondents selected 3 in the range of 1–5 most often, resulting in an average of 3.31. Environmental value has a positive impact on consumers' purchasing behaviour, but their cognitive value prompts them to show hesitation in accepting sustainable products (Khan & Mohsin, 2017). Consumers' negative perceptions of food wastewater hinder the development of environmental awareness. Compared with curiosity and environmental awareness, the average score of prices is relatively high (3.53), showing that low prices seem to be more effective in attracting consumers, but obviously, consumers do not pay too much attention to the economic loss of food. Among four aspects, food safety is the first choice of consumers. The result shows a higher average value (3.99) than the other three aspects, which is close to 4. Consumers' attitudes toward product safety is the same as the result of water quality safety issues. What is interesting is that none of the 135 respondents chose option 1, which proves that food safety can increase consumer acceptance of whey products. Consumers' desire to buy will be motivated while ensuring food safety. Lease et al. (2014) recovered and treated wastewater to meet drinking water standards, and then applied it to meat food, which gained high consumer acceptance. Acid whey and tofu whey have a higher safety factor than other wastewater, but consumers'negative attitudes toward whey wastewater is a problem that needs to be solved. In general, consumers do not have a high degree of acceptance of new whey products, and most of them hold a conservative attitude.

The survey results are mainly due to consumers' risk perception of acid whey and tofu whey. Similarly, research has shown that one of the important hindrances to the implementation of water reuse is consumers' risk perception (Meneses et al., 2017). Consumers obtain information on food safety issues from social network sites, news, or magazines, but fail to think deeply about the true source of food pollution, leading to a negative attitude toward the reuse of food wastewater (Machado Nardi et al., 2020). Reducing risk perception is very significant to increase the recognition and acceptance of whey products. In terms of food risk perception, consumers have a higher perception of experience risk, psychological risk, and health risk (Carducci et al., 2019). They are desperately focused on the quality and characteristics of the product, and care about the emotion produced by the product (Khan & Mohsin, 2017). Their purchase intention also depends on the emotions of consumers (Liang et al., 2019). Functional foods have nutrition as their basic attribute, while hedonic foods that satisfy the need for taste are the main attribute (Machado Nardi et al., 2020). Studies have shown that the acceptance of hedonic foods is higher than functional foods (Madzharov et al., 2016). Making acid whey and tofu whey into palatable pleasure foods seems to effectively reduce food risk perception.

13.3 Food Applications of Whey Ingredients

13.3.1 Acid Whey

Acid whey is a by-product produced during the processing of fermented dairy products such as cottage or quarg cheese and Greek yogurt. According to statistics from the U.S. Department of Agriculture, the production of Greek yogurt in 2021 is about 400 million pounds, an increase of 14% over 2020 (USDA, 2021). For every pound of Greek yogurt produced, approximately 3 pounds of liquid whey waste are produced (Rocha-Mendoza et al., 2020). With increasing sales of Greek yogurt in the US market, the production of acid whey has increased. Acid whey contains more than 93% water, minerals, protein, and lactose-based compounds, but it has a high BOD and COD content (Lievore et al., 2015). Compared with sweet whey, it has a lower content of protein and a higher content of lactose, with the pH value ranging from 4 to 5 (Wherry et al., 2019). The processing of acid whey is considered an additional cost for the dairy industry. However, the treatment of discharging acid whey directly in their waste stream by Greek yogurt manufacturers has been controversial in terms of environmental impact and protection. At present, acid whey is generally used for anaerobic digestion and converted into methane that can generate electricity, which is the best way to treat large amounts of acid whey (Danovich, 2018). It can also be used as crop fertilizer or animal feed (Menchik et al., 2018). In recent years, whey processing has become an emerging industry. Sweet whey has been ultrafiltered by the food processing industry to obtain whey concentrate and spray-dried to produce sweet whey powder, which is widely used in confectionery products, cereal and nutrition bars, processed cheeses, baked goods, sports beverages, muscle gain formulations, and desserts (Prazeres et al., 2012). However, the processing method of sweet whey is not suitable for acid whey, because most of the lactose will be converted into crystal structure due to the high lactic acid content and low pH value during the spray drying (Rocha-Mendoza et al., 2020). However, the nutritional value of acid whey cannot be ignored. Although the development and comprehensive utilization of acid whey are still in the research stages, the potential applications of acid whey as a sustainable product raw material are promising.

The valorization of acid whey is a challenge for dairy industries, but its application in the food processing industry can relieve the pressure of handling large amounts of whey. Although acid whey causes agglomeration of particles during spray drying (Rocha-Mendoza et al., 2020), nanofiltration technology can remove or concentrate 50% of the lactic acid in acid whey to increase the possibility of processing it as a spray-dried whey powder (Chandrapala et al., 2016). Lactose can also be purified from acid whey by ultrafiltration, concentration, and crystallization, and can be used to produce glucose syrup or galactose syrup by enzymatic (such as β-galactosidase) or acid-catalyzed hydrolysis, which can replace sucrose as sweeteners of ice cream, candy, and other foods (Lindsay et al., 2018). It is also a high-quality raw material for the production of fermented probiotic beverages, which provide rich nutrients for lactic acid bacteria (LAB) (Rama et al., 2019). Due to its antibacterial and antioxidant functions, it could become a potential functional beverage (Dragone et al., 2009). It is reported that acid whey can replace all the water in the original fermentation formulation to produce fermented milk because lactose and other solid components provide energy for fermentation, which can shorten the fermentation period and give fermented products a body-full sensory experience (Lievore et al., 2015). Since there is little casein in acid whey, replacing part of the milk with acid whey will reduce the gel strength and viscosity of the fermented product (Lievore et al., 2015). In addition, it can be used to produce a new type of alcoholic beverage with acceptable organoleptic properties by yeast (Dragone et al., 2009). Moreover, it is considered to be a powerful antioxidant and can inhibit the release of iron during the oxidation and deterioration of sausage production to stabilize the bright red colour of sausages (Wójciak et al., 2014). The food applications of acid whey can bring economic benefits to the dairy industry, and be beneficial to consumers' health.

13.3.2 Tofu Whey

Tofu whey contains nutrients such as protein, minerals, monosaccharides, oligosaccharides, and soy isoflavones (Chua & Liu, 2019). Among them, the anticancer factor trypsin inhibitor can effectively prevent liver cancer, colon cancer, and breast cancer (Kobayashi et al., 2004). Every 1 kg of soybeans can produce about 9 kg of tofu whey during tofu processing (Chua et al., 2018). It will promote the growth of microorganisms, resulting in high levels of BOD (8,000–10,000 mg/L) and COD (17,000–26,000 mg/L) when discharged as waste without treatment (Chua & Liu, 2019). The protein and soluble sugar in tofu whey give it a high spoilage rate and consume oxygen in the water and pollute sewers. With the increasing acceptance of tofu by consumers, the risk of environmental pollution continues to increase (Wang & Serventi, 2019). Although tofu whey is rich in nutrients, most of it will be used as crop fertilizer, animal feed, or directly treated as wastewater (Meneses et al., 2017). As a feed, it can provide more nutrition for animals, reduce human competition for feed and the cost of animal products, and reduce the water footprint. However, anaerobic treatment and aerobic treatment cannot recycle the effective ingredients in tofu whey (Hongyang et al., 2011). Using tofu whey to make new products can improve the utilization of nutrients and reduce environmental pollution.

Studies have shown that tofu whey can be used as a culture medium for LAB during sauerkraut fermentation (Cai et al., 2013). It can also be used to produce the next batch of tofu because the fermented tofu whey contains the strong acid-producing *Lactobacillus plantarum* strain JMC-1, which can coagulate soy milk and make the tofu moderate in firmness (Chua & Liu, 2019). Water kefir is a natural starter, and its microbiota includes LAB, yeast, and acetic acid bacteria. It can convert tofu whey into a biologically active beverage that has the function of scavenging free radicals and generating flavonoids, biologically active peptides, and glycerophospholipids that are beneficial to human health (Azi et al., 2021). Kombucha consortium can also convert tofu whey into a potential new functional beverage, which is composed of tea fungus, bacteria, and yeast. Studies have proven that the DPPH scavenging activity and antibacterial activity of tofu whey fermented by the kombucha consortium is improved, and the beany taste is reduced (Tu et al., 2019). Tofu whey, like acid whey, can be made into alcoholic beverages. Both *Saccharomyces cerevisiae* and non-*Saccharomyces cerevisiae* can be used to ferment tofu whey, showing different flavour characteristics (Chua et al., 2021). Researchers at the National University of Singapore (NUS) successfully developed the fermented tofu whey into an alcohol-containing beverage product, namely Sachi, which is rich in isoflavones and antioxidants and has attracted widespread attention worldwide (Chua et al., 2018). In addition, tofu whey can be dried into powder by a vacuum freeze dryer and mixed with flour to make wheat bread, resulting in improving the protein and nutritional quality of the bread, reducing the baking loss, and increasing the total phenols and flavonoid content (Barukčić et al., 2019). The mentioned food applications show that tofu whey is a potential functional food raw material. However, there are currently few sensory studies on the manufacturing of tofu whey into edible food and beverage products, thus, this will be the next research direction to obtain more realistic sensory data from the mass market.

13.4 Conclusion

Eco-environmental resources are allocated globally, and benefits are shared globally. The use of eco-environmental resources by a country or region often affects the well-being of people in all countries. For example, climate warming will not lead to the collapse of Earth itself, but will devastate the fragile human beings, and even make the whole of human society disappear. People have promoted the slogan of “protecting the earth”, but what they really need to protect is our own community and our shared future. The depletion of the ozone layer, climate warming, dramatic decline in biodiversity, and global transport of persistent organic pollutants represent the primary challenges facing the community of shared future of mankind. All countries must join in addressing these challenges. No single country, region, or organization can lead such a large-scale global ecological and environmental governance action alone. The ecological and environmental crisis must and can only be resolved through the organization of a community of shared future for humans. As a community, humankind must respect, conform to, and protect nature. The sustainable development of a community with a shared future will only be possible if all countries in the world make positive changes and embark on the path of green development.

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References

Adams, D. C., Allen, D., Borisova, T., Boellstorff, D. E., Smolen, M. D., & Mahler, R. L. (2013). The influence of water attitudes, perceptions, and learning preferences on water-conserving actions. *Natural Sciences Education, 42*(1), 114–122.

Azi, F., Tu, C., Meng, L., Zhiyu, L., Cherinet, M. T., Ahmadullah, Z., & Dong, M. (2021). Metabolite dynamics and phytochemistry of a soy whey-based beverage bio-transformed by water kefir consortium. *Food Chemistry, 342*, 128225.

Barukčić, I., Jakopović, K. L., & Božanić, R. (2019). Whey and buttermilk—neglected sources of valuable beverages. In *Natural beverages* (pp. 209–242). Elsevier.

Cai, T., Park, S. Y., & Li, Y. (2013). Nutrient recovery from wastewater streams by microalgae: Status and prospects. *Renewable and Sustainable Energy Reviews, 19*, 360–369.

Carducci, A., Fiore, M., Azara, A., Bonaccorsi, G., Bortoletto, M., Caggiano, G., & Ferrante, M. (2019). Environment and health: Risk perception and its determinants among Italian university students. *Science of the Total Environment, 691*, 1162–1172. https://doi.org/10.1016/j.scitotenv.2019.07.201

Casani, S., Rouhany, M., & Knøchel, S. (2005). A discussion paper on challenges and limitations to water reuse and hygiene in the food industry. *Water Research, 39*(6), 1134–1146. https://doi.org/10.1016/j.watres.2004.12.015

Cassano, A., Rastogi, N., & Basile, A. (2015). Membrane technologies for water treatment and reuse in the food and beverage industries. In *Advances in membrane technologies for water treatment* (pp. 551–580). Elsevier.

Chandrapala, J., Duke, M. C., Gray, S. R., Weeks, M., Palmer, M., & Vasiljevic, T. (2016). Nanofiltration and nanodiafiltration of acid whey as a function of pH and temperature. *Separation and Purification Technology, 160*, 18–27.

Chua, J.-Y., & Liu, S.-Q. (2019). Soy whey: More than just wastewater from tofu and soy protein isolate industry. *Trends in Food Science and Technology, 91*, 24–32.

Chua, J.-Y., Lu, Y., & Liu, S.-Q. (2018). Evaluation of five commercial non-saccharomyces yeasts in fermentation of soy (tofu) whey into an alcoholic beverage. *Food Microbiology, 76*, 533–542.

Chua, J.-Y., Tan, S. J., & Liu, S.-Q. (2021). The impact of mixed amino acids supplementation on Torulaspora delbrueckii growth and volatile compound modulation in soy whey alcohol fermentation. *Food Research International, 140*, 109901.

Coppola, A., & Verneau, F. (2018). Food Neophobia in consumers. In *Reference module in food science*. Elsevier.

Danovich, T. (2018). *One pound of cheese makes nine pounds of whey. Where does it all go?*. Retrieved from https://thecounter.org/whey-disposal-reuse-cheese-dairy-byproduct/

Dragone, G., Mussatto, S. I., Oliveira, J. M., & Teixeira, J. A. (2009). Characterisation of volatile compounds in an alcoholic beverage produced by whey fermentation. *Food Chemistry, 112*(4), 929–935.

Eck, C. J., Wagner, K. L., Chapagain, B., & Joshi, O. (2019). A survey of perceptions and attitudes about water issues in Oklahoma: A comparative study. *Journal of Contemporary Water Research & Education, 168*(1), 66–77.

FDA. (2017). *Food code*. Retrieved from https://www.fda.gov/food/fda-food-code/food-code-2017

Gerrath, M. H. E. E., & Biraglia, A. (2021). How less congruent new products drive brand engagement: The role of curiosity. *Journal of Business Research, 127*, 13–24. https://doi.org/10.1016/j.jbusres.2021.01.014

González, N., Marquès, M., Nadal, M., & Domingo, J. L. (2020). Meat consumption: Which are the current global risks? A review of recent (2010–2020) evidences. *Food Research International, 137*, 109341. https://doi.org/10.1016/j.foodres.2020.109341

Hogeboom, R. J. (2020). The water footprint concept and Water's grand environmental challenges. *One Earth, 2*(3), 218–222. https://doi.org/10.1016/j.oneear.2020.02.010

Hongyang, S., Yalei, Z., Chunmin, Z., Xuefei, Z., & Jinpeng, L. (2011). Cultivation of Chlorella pyrenoidosa in soybean processing wastewater. *Bioresource Technology, 102*(21), 9884–9890.

Khan, M. N., & Mohammad, F. (2014). Eutrophication: Challenges and solutions. In *Eutrophication: causes, consequences and control* (pp. 1–15). Springer.

Khan, S. N., & Mohsin, M. (2017). The power of emotional value: Exploring the effects of values on green product consumer choice behavior. *Journal of Cleaner Production, 150*, 65–74. https://doi.org/10.1016/j.jclepro.2017.02.187

Kobayashi, H., Suzuki, M., Kanayama, N., & Terao, T. (2004). A soybean Kunitz trypsin inhibitor suppresses ovarian cancer cell invasion by blocking urokinase upregulation. *Clinical & Experimental Metastasis, 21*(2), 159–166.

Lease, H., MacDonald, D. H., & Cox, D. (2014). Consumers' acceptance of recycled water in meat products: The influence of tasting, attitudes and values on hedonic and emotional reactions. *Food Quality and Preference, 37*, 35–44.

Liang, D., Hou, C., Jo, M.-S., & Sarigöllü, E. (2019). Pollution avoidance and green purchase: The role of moral emotions. *Journal of Cleaner Production, 210*, 1301–1310. https://doi.org/10.1016/j.jclepro.2018.11.103

Lievore, P., Simões, D. R., Silva, K. M., Drunkler, N. L., Barana, A. C., Nogueira, A., & Demiate, I. M. (2015). Chemical characterisation and application of acid whey in fermented milk. *Journal of Food Science and Technology, 52*(4), 2083–2092.

Lindsay, M. J., Walker, T. W., Dumesic, J. A., Rankin, S. A., & Huber, G. W. (2018). Production of monosaccharides and whey protein from acid whey waste streams in the dairy industry. *Green Chemistry, 20*(8), 1824–1834.

Machado Nardi, V. A., Teixeira, R., Ladeira, W. J., & de Oliveira Santini, F. (2020). A meta-analytic review of food safety risk perception. *Food Control, 112*, 107089. https://doi.org/10.1016/j.foodcont.2020.107089

Madzharov, A. V., Ramanathan, S., & Block, L. G. (2016). The halo effect of product color lightness on hedonic food consumption. *Journal of the Association for Consumer Research, 1*(4), 579–591.

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences, 15*(5), 1577–1600.

Mekonnen, M. M., & Hoekstra, A. Y. (2012). A global assessment of the water footprint of farm animal products. *Ecosystems, 15*(3), 401–415.

Menchik, P., Zuber, T. J., Zuber, A., & Moraru, C. (2018). *The acid whey conundrum*. Retrieved from https://www.dairyfoods.com/articles/92849-the-acid-whey-conundrum

Meneses, Y. E., Stratton, J., & Flores, R. A. (2017). Water reconditioning and reuse in the food processing industry: Current situation and challenges. *Trends in Food Science and Technology, 61*, 72–79. https://doi.org/10.1016/j.tifs.2016.12.008

Meneses, Y. E., Martinez, B., & Hu, X. (2019). Water reconditioning in the food industry. In *Sustainable water and wastewater processing* (pp. 329–365). Elsevier.

Moosavi, S., Browne, G. R., & Bush, J. (2021). Perceptions of nature-based solutions for urban water challenges: Insights from Australian researchers and practitioners. *Urban Forestry & Urban Greening, 57*, 126937. https://doi.org/10.1016/j.ufug.2020.126937

Nezlek, J. B., Forestell, C. A., & Cypryanska, M. (2021). Approach and avoidance motivation and interest in new foods: Introducing a measure of the motivation to eat new foods. *Food Quality and Preference, 88*, 104111. https://doi.org/10.1016/j.foodqual.2020.104111

NZ Food Data Composition. (2021). Retrieved from https://www.foodcomposition.co.nz/search/food/C1127/nip.

Petrescu, D. C., Petrescu-Mag, R. M., Manciula, D. I., Nistor, I. A., & Ilieş, V. I. (2019). Wastewater reflections in consumer mind: Evidence from sewage services consumer behaviour. *Sustainability, 11*(1), 123.

Prazeres, A. R., Carvalho, F., & Rivas, J. (2012). Cheese whey management: A review. *Journal of Environmental Management, 110*, 48–68.

Rama, G. R., Kuhn, D., Beux, S., Maciel, M. J., & de Souza, C. F. V. (2019). Potential applications of dairy whey for the production of lactic acid bacteria cultures. *International Dairy Journal, 98*, 25–37.

Rocha-Mendoza, D., Kosmerl, E., Krentz, A., Zhang, L., Badiger, S., Miyagusuku-Cruzado, G., & García-Cano, I. (2020). Invited review: Acid whey trends and health benefits. *Journal of Dairy Science, 104*(2), 1262–1275.

Tiseo, I. (2019). *Global water withdrawal and consumption 2014–2040*. Retrieved from https://www.statista.com/statistics/216527/global-demand-for-water/

Tiseo, I. (2020). *Global key figures on wastewater generation 2020*. Retrieved from https://www.statista.com/statistics/1124488/key-facts-wastewater-generation-globally/

Tu, C., Tang, S., Azi, F., Hu, W., & Dong, M. (2019). Use of kombucha consortium to transform soy whey into a novel functional beverage. *Journal of Functional Foods, 52*, 81–89.

UNESCO. (2016). *International Initiative on Water Quality (IIWQ)*. Retrieved from https://en.unesco.org/waterquality-iiwq/wq-challenge

USDA. (2021). *Dairy products*. Retrieved from https://usda.library.cornell.edu/concern/publications/m326m1757?locale=en

Vanham, D., Mekonnen, M. M., & Hoekstra, A. Y. (2020). Treenuts and groundnuts in the EAT-lancet reference diet: concerns regarding sustainable water use. *Global Food Security, 24*, 100357.

Wang, Y., & Serventi, L. (2019). Sustainability of dairy and soy processing: A review on wastewater recycling. *Journal of Cleaner Production, 237*, 117821.

Wherry, B., Barbano, D. M., & Drake, M. A. (2019). Use of acid whey protein concentrate as an ingredient in nonfat cup set-style yogurt. *Journal of Dairy Science, 102*(10), 8768–8784.

Winpenny, J., Heinz, I., Koo-Oshima, S., Salgot, M., Collado, J., Hernandez, F., & Torricelli, R. (2010). The wealth of waste: The economics of wastewater use in agriculture. *Water Reports, 35,* 129 pp.

Wójciak, K. M., Karwowska, M., & Dolatowski, Z. J. (2014). Use of acid whey and mustard seed to replace nitrites during cooked sausage production. *Meat Science, 96*(2), 750–756.

Xie, Y.-X., Xiong, Z.-Q., Xing, G.-X., Sun, G.-Q., & Zhu, Z.-L. (2007). Assessment of nitrogen pollutant sources in surface waters of Taihu Lake Region1 1Project supported by the state key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences (no. 035109) and the National Natural Science Foundation of China (no. 30390080). *Pedosphere, 17*(2), 200–208. https://doi.org/10.1016/S1002-0160(07)60026-5

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