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Review

Dietary Fiber from Plant-Based Food Wastes: A Comprehensive Approach to Cereal, Fruit, and Vegetable Waste Valorization

Sofia Plakantonaki [1,*], Ioannis Roussis [2], Dimitrios Bilalis [2] and Georgios Priniotakis [1]

[1] Department of Industrial Design and Production Engineering, University of West Attica, 12244 Aigaleo, Greece; gprin@uniwa.gr
[2] Laboratory of Agronomy, Department of Crop Science, Agricultural University of Athens, 11855 Athens, Greece; roussis@aua.gr (I.R.); bilalis@aua.gr (D.B.)
* Correspondence: splakantonaki@uniwa.gr

Abstract: The agri-food industry generates significant quantities of plant-based food waste from processing, which offers a valuable research opportunity aimed at minimizing and managing these wastes efficiently in support of zero waste and/or circular economies. In order to achieve food security, all of these wastes can be valorized using downstream processes in an integrated manner, which results in the conversion of waste into secondary raw materials. Specifically, plant-based food wastes and/or byproducts are recognized sources of bioactive chemicals, including dietary fibers that are beneficial as food additives or functional food ingredients that can meet the technological and functional requirements of health-promoting value-added products. Additionally, cellulosic ingredients can be utilized directly within nonfood industries, such as textiles, resulting in a reduction in the environmental impact of secondary raw materials, as well as an increase in market acceptance compared to those currently on the market. On this basis, the present review was designed to provide an overview of introducing novel concepts for effective reuse, recyclability, and maximal utilization of plant-based food wastes and/or byproducts from food-processing industries, which creates a potential opportunity for the extraction of value-added dietary fiber with potential applications in food and nonfood industries.

Keywords: agri-food waste; agro-polymers; cellulose; circular economy; insoluble dietary fibers (IDF); food products; textiles

Citation: Plakantonaki, S.; Roussis, I.; Bilalis, D.; Priniotakis, G. Dietary Fiber from Plant-Based Food Wastes: A Comprehensive Approach to Cereal, Fruit, and Vegetable Waste Valorization. *Processes* **2023**, *11*, 1580. https://doi.org/10.3390/pr11051580

Academic Editors: Jelena T. Petrović and Marija Simic

Received: 26 April 2023
Revised: 17 May 2023
Accepted: 20 May 2023
Published: 22 May 2023

1. Introduction

Each year, one-third of all food produced for human consumption is lost or wasted along the production chain, thus affecting the sustainability of food systems and their capability to ensure food and nutrition security. Food loss is defined as the decrease in quantity or quality of food reflected in nutritional value, economic value, or food safety of all food produced for human consumption that is not consumed by humans. On the other hand, food waste constitutes a part of food loss, which refers to disposing of or utilizing food in alternative ways throughout the entire food supply chain [1]. Food waste is produced due to high production rates combined with inefficient handling technologies. Global food losses and waste average about 30% for cereals, 40–50% for root crops, fruits, and vegetables, and 20% for oilseeds, meat, and dairy [1] (Figure 1). This waste of natural resources has a huge impact on the environment, including increased carbon dioxide emissions, soil and water pollution, and increased food insecurity. It is estimated that reducing global food waste would reduce global greenhouse gas emissions by 8% [2]. As food is produced, handled, stored, processed, distributed, and consumed, there are a variety of stages at which waste is generated [2–4]. The biggest food loss occurs at the farm level [5]. For instance, in the United States of America, 9.2 billion kilograms of food is lost every year on farms [6]. Food industries suffer extensive food loss and waste during processing. Some of these losses occur during transportation or as a function of non-appropriate transportation systems, due to problems during storage, processing, or contamination, and from inappropriate packaging [7]. The main causes of food loss and waste at the market level are an erratic method of handling and/or conserving food, and a lack of refrigeration or cold storage [2]. Furthermore, there is a considerable amount of food wasted at the consumer level as a result of excessive or inappropriate purchases, poor storage conditions, overpreparation, portioning, cooking, etc. [4,8,9].

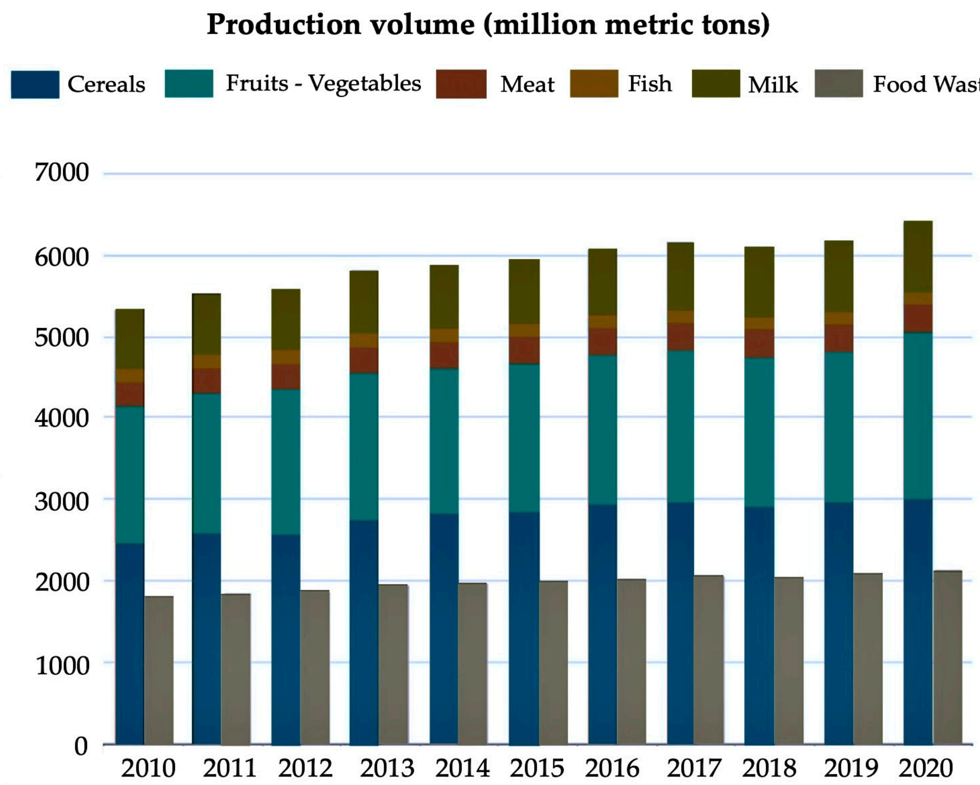

Figure 1. Global food production and estimated food waste generated over the period 2010–2020. The graph was prepared from data retrieved from [10].

Globally, approximately one-third of the world's total food production (1.4 billion metric tons) is wasted each year, according to the Food and Agriculture Organization of the United Nations (FAO) [11]. The amount of food waste produced in developed countries is higher than developing and undeveloped countries [12]. In Europe and North America, food loss is 280–300 kg per year. It ranges from 120 to 170 kg per year in sub-Saharan Africa and South/Southeast Asia. In Europe and North America, 900 kg of edible food components are produced per person annually, compared to 460 kg in sub-Saharan Africa and 460 kg in South and Southeast Asia [7] (Figure 2). Europe and North America create 95 to 115 kg of food waste each year per capita. In contrast, only 6–11 kg is generated in sub-Saharan Africa and South/Southeast Asia [7] (Figure 3). Food waste has a high prevalence in medium- and high-income countries due to the discarding of edible food. Low-income countries experience this loss most frequently during production and processing [7,13].

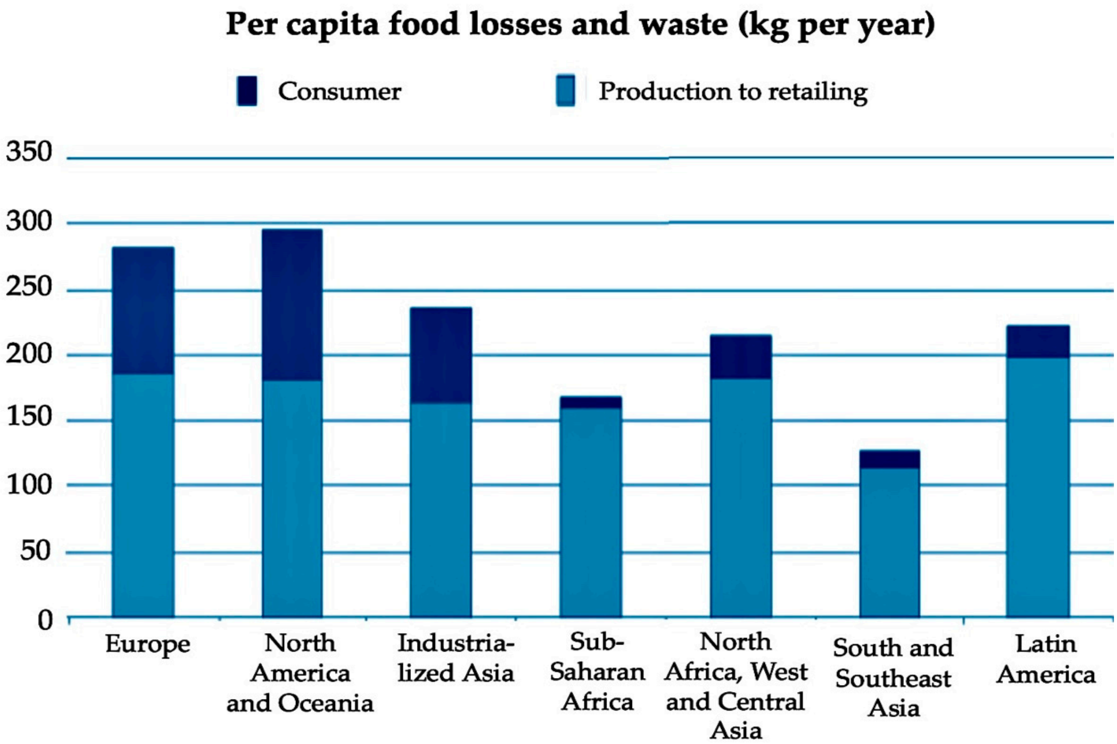

Figure 2. Food losses and waste per capita, by region, during consumption and pre-consumption stages. The graph was prepared from data retrieved from Food Loss and Waste Database of the Food and Agriculture Organization of the United Nations (FAO) (https://www.fao.org/platform-food-loss-waste/flw-data/en/) (accessed on 31 March 2023).

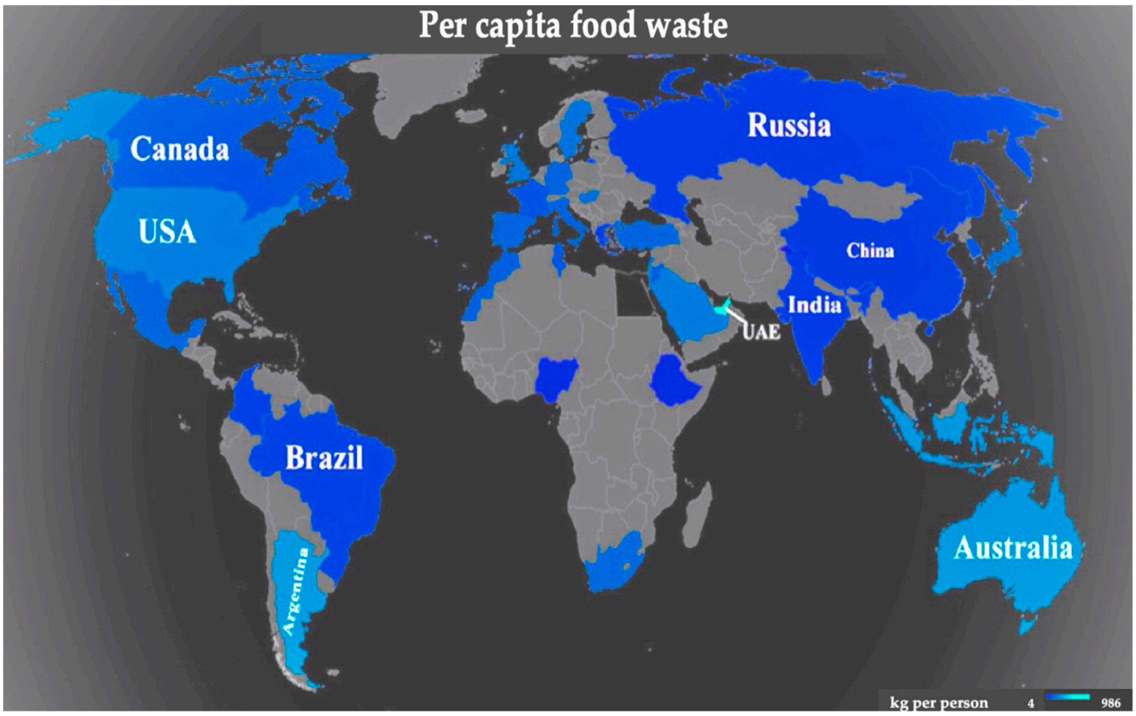

Figure 3. Global distribution of food waste per capita per year (in kilograms per person per year). The map was prepared from data retrieved from Food Sustainability Index 2017 (https://impact.economist.com/projects/foodsustainability/) (accessed on 31 March 2023).

It is important to recognize that food waste is a comprehensive and multidimensional issue that affects all stages of the food supply chain, from the primary production of food to its final consumption. It is estimated that billions of euros are spent each year on the treatment of agricultural and food waste in order to reduce the risks to humans, animals, and the environment. As a result of food waste being disposed of in landfills, methane gas is produced in large quantities, which is harmful to the environment [14,15]. Incineration produces harmful air pollution, as well as chemical loss. There is a complex interplay among food waste, water and energy resources, environmental quality, and social justice, which makes it a quite significant problem that requires immediate attention from the individual to the global level [16], as well as appropriate management [13,17]. Food waste elimination is difficult, but not impossible. While food waste is a significant issue, there are several ways to reduce it and to find an effective and beneficial use for it.

A new research area has been opened in this regard aimed at minimizing and managing food waste more efficiently in order to support the concept of zero waste. Consequently, a number of projects are required to encourage upstream waste recovery, leading to the production of downstream value-added ingredients, always in accordance with a circular economy [15]. In order to ensure the future application of the ingredients resulting from this process, several previous steps must be taken to ensure a successful integrated recovery and take into account the complexities of food safety.

In order to achieve food security, all of these wastes can be valorized using downstream processes in an integrated manner, which results in the conversion of waste into secondary raw materials. Specifically, plant-based food wastes and/or byproducts are recognized sources of bioactive chemicals, including dietary fibers that are beneficial to health [7,13]. There are several health benefits associated with dietary fiber, including lowering blood cholesterol and blood sugar levels, as well as improving cardiovascular health [12]. However, dietary fiber shows considerable potential as a food additive or functional food ingredient that can meet the technological and functional requirements of health-promoting value-added products [7,12]. Additionally, cellulosic ingredients can be utilized directly within nonfood industries, such as paper, biodiesel, and textiles, as well as in sustainable packaging, resulting in a reduction in the environmental impact of secondary raw materials, as well as an increase in market acceptance compared to those currently on the market [13].

Thus, this review provides an overview of novel concepts for maximizing the potential of plant-based food wastes and/or byproducts produced in the food-processing industries in terms of effective reuse, recyclability, and optimal utilization. In addition, this study emphasizes the potential opportunity for the extraction of value-added dietary fiber from the abovementioned wastes and/or byproducts and their possible applications in the food and nonfood industries.

2. Valorization of Plant-Based Food Wastes

By using valorization technology, plant-based food waste can be converted into value-added products. Plant-based food wastes are typically underutilized and have only limited applications as bio-compost or biofuel [2]. The fact remains that, if plant-based food waste is left untreated for an extended period, it can cause serious environmental damage, leading to foul odors and air pollution. Several studies have demonstrated that plant-based food wastes are a valuable source of functional bioactive compounds [18]. It has been reported that most of these bioactive compounds have beneficial health effects, including antioxidant, antibacterial, antitumor, and cardioprotective properties [19–21]. Food-processing industrial wastes contain many bioactive compounds (such as dietary fibers, pigments, minerals, fatty acids, and antioxidant polyphenolic compounds) that must be extracted using environmentally friendly methods. These compounds have potential applications in the pharmaceutical and food industries, making their extraction a worthwhile endeavor. To achieve this, traditional methods of solvent extraction are being replaced by green technologies such as supercritical fluid extraction and ultrasound-assisted extraction. These technologies are more efficient and produce fewer hazardous residues, making them the preferred choice for the extraction of bioactive compounds [22].

Dietary fibers are primarily carbohydrate polymers, such as cellulose, hemicellulose, lignin, and pectin, which provide plant cell walls with structural rigidity. Several types of dietary fibers can be extracted from waste from cereal, fruit, and vegetable processing [23]. Dietary fibers are classified on the basis of their water solubility into soluble dietary fiber (SDF) and insoluble dietary fiber (IDF). Pectins (found in whole grains, legumes, etc.), gums (found in legumes, etc.), and mucilage (found in aquatic plants, aloe vera, okra, and glycoproteins from food additives) are examples of soluble dietary fibers, while cellulose (which provides glucose monomers that are found in fruits, roots, and grains), hemicellulose (complex sugars found in cereal bran and grains), and lignin (aromatic alcohols found in vegetables) are examples of insoluble dietary fibers [13,23]. There are several methods for extracting dietary fiber fibers (SDF and/or IDF), including dry and wet processing, chemical methods, enzymatic gravimetric methods, and microbial methods (albeit with some limitations) [20]. In addition, a number of green extraction techniques have also been developed over the past few years, including water extraction, ethanol extraction, steam extraction, pulsed electric field-assisted extraction, ultrasonic-assisted extraction, high hydrostatic pressure-assisted extraction, and other combinations of methods [24,25].

Various techniques have been used to extract dietary fibers from plant resources. There is a correlation between the extraction methods used (e.g., drying and solvent extraction), the intensity of treatment, and the composition and characteristics of the fibers obtained [26]. The choice of extraction method depends on factors such as the chemical nature of the fiber, its composition, and its complexity [20]. Among the factors that can influence the yield of dietary fiber are the ratio of liquid to solid, the duration of contact time, the temperature, and the selected method of extraction [27]. Different extraction techniques have varied effects on the molecular structure of dietary fibers. Alkali- and acid-based extraction techniques can damage the molecular structure, while enzymatic-assisted extraction techniques may result in incomplete extraction. Alkali- and acid-based extraction techniques can cause the breakdown of the bonds between the fiber molecules, resulting in reduced fiber quality. Enzymatic-assisted extraction techniques can also cause incomplete extraction, leaving some of the fiber molecules bound together and unable to be extracted [20,24]. Combining enzymatic and solvent extraction methods can also be useful for the extraction of dietary fibers. Additionally, modified wet-milling methods have been recommended for better extractability, due to their cost effectiveness, ability to produce high-purity fiber, and use of reduced amounts of chemicals and water compared to other regular methods. According to studies, the purity of dietary fiber obtained by wet milling is between 50% and 90% [20].

A review of current processing techniques is provided in the literature, including pulsed electric field, ultrasonic, microwave, high hydrostatic pressure, and ionizing radiation. Each of these techniques has both advantages and disadvantages. The use of these novel, sustainable, and green extraction technologies promotes high-quality extraction that is reproducible, simple to handle, and environmentally friendly. These technologies use less energy and fewer resources than traditional extraction methods, thus reducing their environmental impact. They also result in better-quality extracts with higher levels of purity and fewer contaminants [24,28]. For instance, using an ultrasonic-aided extraction approach, Wang et al. [29] recovered hemicellulose and phenols from bamboo 'bast fiber' powder. An 2.6-fold increase in extraction efficiency was achieved through the combination of ultrasonic extraction and hot water treatment. Additionally, it facilitated the biosynthesis of polyphenolic chemicals, hemicellulose, and lignin [29]. However, modern extraction methods can have disadvantages, such as excessive energy consumption (e.g., microwave extraction), separation challenges (e.g., ultrasonic technique), and user incompatibility (e.g., pulsed electric field technique). Microwave extraction requires a significant amount of energy, which can be expensive to use and difficult to scale up. Ultrasonic techniques can struggle with separating the desired compounds from the remainder of the sample, and pulsed electric fields can be difficult for users to operate, making it hard to control the quality of the extracted products [24]. Considering the abovementioned factors, wet milling has been identified as a suitable extraction method due to its low cost and ability to produce high-quality pure fibers. Wet milling reduces the time required for the extraction process and increases the purity of the fibers. It also has the potential to reduce the amount of energy required for the process and can be conducted at a relatively low cost [7,13].

3. Utilization of Plant-Based Food Wastes and Byproducts on Circular Economy

Plant-based food wastes and/or byproducts, especially in the industrial sector, must be managed in a sustainable manner in order to minimize the high volumes accumulated in landfills. It is crucial to develop innovative approaches for their effective reuse and recyclability in order to ensure a successful monetization of these materials and to increase their economic value indirectly. It was noted by the European Environment Agency (EEA) that the development of resource-efficient, low-carbon economies and societies by the year 2050 is an essential milestone to achieve. Consequently, a worldwide trend must be explored for possible pathways toward a circular economy (CE) transition [15]. In a linear economy, raw materials are the main components of economic development, whereas they are taken, processed, consumed, and disposed of as waste [15]. As part of a circular economy, the recovery and valorization of waste allow for the reuse of materials and the return of those materials to the supply chain, thereby allowing economic growth from environmental loss [30].

Using plant-based food wastes and byproducts to their full potential will certainly have a positive impact on the circular economy since they contain valuable bioactive compounds, including dietary fibers with diverse bioactivities. The European Union alone generates more than 88 metric tons of organic agricultural waste [4], most of which is disposed of in landfills. The successful management of waste or byproducts can be viewed as a positive step toward transitioning from a linear economy to a circular economy [20]. Furthermore, it is imperative to utilize creative approaches when improving upstream recovery processes of wastes, which ultimately leads to the production of value-added compounds, all of which are in line with the concept of a sustainable circular economy [15].

Utilizing plant-based waste within a circular economy system allows commodities to be recycled or reused, and then reintroduced into the supply chain, which in turn promotes economic growth and minimizes environmental impact [30]. Furthermore, there is enormous potential for using waste and byproducts created by the agri-food industry to create value-added products that are low-cost, such as biorefinery fragments, fuel, enzymes, flavorings, natural pigments, and health-promoting components such as dietary fiber. Additionally, they can be critical components in both the food and the nonfood industries [22,31,32]. As a result of all these factors, waste minimization, effective use, and zero-waste concepts can be achieved.

In the available literature, there is limited information regarding life cycle assessments (LCAs), social life assessments (s-LCAs), and life cycle costings (LCCs) of agro-industrial waste-based biorefineries [15,33]. To achieve a sustainable goal, more research is needed to examine the social and economic aspects of the proposed strategy over a longer period of time. As a result of the lack of demand for agro-industrial waste-based methods (primarily due to a lack of commercialization and public awareness) and financial constraints, these technologies cannot be commercially demonstrated [34]. Several factors restrict the availability of agro-industrial wastes for industrial processes, including logistic issues, technological constraints, and seasonal variations. Due to the lack of clear policy guidelines even in developed countries, the importance of agro-industrial waste biorefineries is further diminished. In the absence of clear technical standards for biobased products derived from agro-industrial waste, the ability of these processes to penetrate a commercial market is often complicated [35,36]. In addition, the lack of public awareness of biobased products may hinder their profitability.

The concept of agro-industrial waste-based biorefineries and the migration toward a circular economy are viewed as sustainable and futuristic approaches to waste management and waste valorization. There is a research gap between clear policies and guidelines for agro-industrial waste management and valorization. This gap should be bridged through the involvement of policymakers, stakeholders, and the general public [15,34]. Ultimately, zero-waste production can only be achieved by integrating various production processes. In order to address the barriers associated with their sustainable valorization and transformation, as well as create the structure for a circular economy based on agro-industrial wastes, it is imperative to broaden our perspective on agro-industrial wastes as potential resources rather than treating them as trash [33,35,36].

4. Dietary Fiber from Plant-Based Food Wastes

4.1. Cereals

4.1.1. Wheat

According to the FAO, approximately 750 million tons of wheat is produced worldwide on an annual basis. Wheat is mainly cultivated in Europe, North America, and Asia, especially in China and India, which are the two largest producers in the developed world [37]. In addition, the FAO has commissioned studies indicating that 30% of cereals are lost or wasted globally each year [1]. There is a range of 9–20% dietary fiber found in wheat, which comprises both soluble and insoluble constituents [38,39].

Arabinoxylan and β-d-glucan are the two main forms of dietary fiber components that make up the cell walls of the starchy endosperm cells in wheat. Small quantities of cellulose and glucomannans may also be present in these cell walls [40]. The wheat endosperm typically has a very low cellulose content (<5%) [39]. A highly insoluble network of cellulose molecules is created by the association of cellulose molecules, which are linear polymers of β-(1→4)-linked glucose units [38]. Arabinoxylan and mixed linked β-glucan make up approximately 70% and 20%, respectively, of the total dietary fiber composition. In grains, hemicellulose is a common form of DF. Heterogenous polysaccharides make up hemicellulose, the non-cellulosic portion of cell walls [41]. The four main types of hemicellulose molecules are xylans, xyloglucans, glucomannans, and mixed-linkage β-glucans [41].

When wheat straw was treated with 2% H_2O_2 at 50 °C and pH 11.5 for 4 ± 30 h or with 2% H_2O_2 ± 0.05% anthraquinone at 50 °C and pH 11.5 for 4.5 h, the original lignin and hemicelluloses were respectively solubilized to 79–86% and 77–91% of their original amounts [42]. Wheat straw lignin and hemicellulose yields were higher from ultrasonically aided extraction than from the traditional alkali method [43]. Extrusion cooking had a beneficial influence on total and soluble dietary fiber and a negative effect on insoluble dietary fiber, according to surface methodology that was optimized with the extrusion parameter [44]. Alkali (2% NaOH) and proteinase were used to remove the dietary fiber from wheat bran, yielding a dietary fiber that was comparatively pure [45].

4.1.2. Maize

An average of 1127 million tons of maize is produced worldwide each year [37]. North America is the leading producer of maize, followed by Asia, especially East Asia. Farmers in areas with limited land and high population pressure are particularly attracted to it because of its high yields (compared to other cereals) [46]. The production of maize is primarily used for livestock feed, with only 13% of it being consumed by humans [47].

Grain maize has a dietary fiber content that ranges from 3.7% to 19.9% [48,49], with IDF accounting for the majority of this content [50]. The two main IDF parts in maize bran are hemicellulose and cellulose [49]. Specifically, in dry and wet milling, maize hulls are inexpensive byproducts that are composed of hemicelluloses (30–50%), cellulose (~20%), phenolic acids (~4%, mainly ferulic and ferulic acid), starch (9–23%), proteins (10–13%), lipids (2%), and ash (2%) [51–53].

Working on the nutritional composition of maize stover, Li et al. [54] discovered considerable changes in fiber concentration. The goal of this research was to uncover potential use for maize stover as a ruminant feed. When compared to other maize stover fractions, the ear husk, leaf blade, and stem pith had the highest nutritious content. As a result, the leaf blade had the lowest percentage of neutral detergent fiber and acid detergent fiber, at 62% and 31%, respectively. The stem rind, on the other hand, had a high acid detergent fiber and acid detergent lignin content of ~48% and 8%, respectively. Moreover, the ear husk had a neutral detergent fiber content of around 83% and a 3.6% acid detergent lignin content. The maximum yield of dietary fiber A in defatted maize husk was produced by hot-compressed water at 150 °C for 60 min [53]. As the temperature climbed from 110 to 180 °C, the yield of dietary fiber B increased from 2.0% to 56.9%, whereas the yield of solid residue reduced from 88.7% to 27.7% [53].

4.1.3. Rice

The average yearly production of rice in the world is 755.4 million tons. With an annual production of 211.4 million tons, China is the world's greatest producer of rice. With 177.6 million tons produced annually, India stands in second. Together, China and India produce more than 50% of the world's rice [37].

The whole grain of rice has a total dietary fiber level that ranges from 2.7% to 9.9%. This wide range in dietary fiber content is partly explained by variations in rice types [41,55]. There is less nutritional fiber in white rice than in brown rice, since the outer kernel layers have been removed by abrasive milling. Similarly to other cereal grains, rice kernels contain a significant amount of dietary fiber in their hull and bran [56]. In the whole grain of rice, cellulose and water-insoluble hemicellulose are the main constituents of the IDF fraction, whereas the SDF fraction consists of soluble arabinoxylan and β-glucan [57].

The primary water-soluble polysaccharides in rice are called glucans, and the alkaline extraction of these polysaccharides from rice husks results in the presence of arabinose, xylose, glucose, and galactose. Among the most prevalent natural polysaccharides, hemicelluloses make up about 30% of the dry matter in rice straw [7]. The invention of a fractionated treatment process for rice straw hemicellulose with maximal yield but little degradation and light color was the outcome of a comparison study of the extraction of rice straw hemicellulose by alkaline and hydrogen peroxide procedures [42].

4.2. Fruits

4.2.1. Apple

According to FAOSTAT data, there were more than 93 million tons of apples produced worldwide in 2021 [33]. About 30% of the apples harvested are processed into juices, ciders, and dried products. It has been estimated that these technological processes produce up to 30% waste, in the form of apple pomace [58]. Pomace is the residue left after the processing of apples, primarily comprising peel and flesh (95%), seeds (2–4%), and stems (1%) [59]. Due to the high number of apple byproducts, different challenges are encountered in terms of transportation and disposal; even so, these wastes can be valuable sources of dietary fibers.

There is evidence that apple peel contains higher levels of dietary fiber than apple pulp. It is estimated that apple pomace contains 15% and 36% soluble and insoluble dietary fiber (on a dry weight basis), respectively [60]. Yan and Kerr [61] reported that vacuum-dried pomace possessed a variable amount of total dietary fiber ranging from 44.2% to 49.5%, and this variation was not significant compared to freeze-dried pomace (48%). It is possible to increase the production of soluble dietary fiber through the use of different extraction techniques. Specifically, a high yield of soluble fiber content can be achieved using ultrasound-assisted extraction techniques in comparison to microwave-assisted extraction or hydrolysis procedures [62].

Products comprising cellulose, pectin, hemicellulose, and lignin have a high water-holding capacity between 9 and 10 g per gram. Bakery goods, dairy goods, medicines, and pet meals are just a few of the applications for these fiber-rich products [63,64]. The use of dried apple fiber in various bakery products was compared with that of oat and wheat bran in a study conducted by Chen et al. [65]. In comparison to oat and wheat bran, apple exhibited a higher total dietary fiber content. According to the composition of apple fiber, 40% of the fiber was cellulose and 19% was water-soluble hemicellulose (on a dry weight basis) [65].

4.2.2. Citrus Fruits

Almost 88 million tons of citrus fruits are produced annually, including oranges, mandarins, limes, and lemons [66]. Citrus fruits are classified as having an acidic flavor because they contain high amounts of citric acid, a potent natural antioxidant. Typically, these fruits are bought from the market and eaten fresh or processed into juices, marmalades, or flavorings. Unfortunately, this industrialization generates a substantial number of citrus byproducts, most frequently peel. With a very low economic impact, it is estimated that more than 10 million tons of citrus fruits are produced only in the European Union [15].

Around 35–37% of the total dietary fiber is made up of orange pulp and peel wastes, which are rich in cellulose and hemicelluloses (17–18%), pectic components up to 17%, and lignin between 2% and 3% (on a dry weight basis) [67,68]. Orange juice included 22% soluble and 54% insoluble dietary fiber from citrus. This fiber had an 11:1 water-binding capacity and an oil-binding capacity of 3–4 g per gram, or three to four times its weight [69]. In addition to being able to provide pulp for drinks (cloudy drinks), orange fiber can also be used as a gelling agent, as a binder for low-calorie bulking, and as a thickener for drinks [70,71]. Dairy goods, infant foods, beverages, soups, fruit juices, and desserts are some of its suggested applications [69,72].

Lemon peels have a total dietary fiber composition of 14%, which is about twice as much as that of peeled lemons (7% on a dry weight basis) [71,73]. Soluble and insoluble fibers made up 5% and 9% of the total amount of dietary fibers, respectively. There are significant levels of soluble and insoluble dietary fibers in lemon pulp and peels. Nonetheless, pulp has significantly more dietary fiber (78%) in comparison to the peel (53%) [73].

4.2.3. Peach

Each year, peaches are harvested in excess of 25 million tons worldwide [37]. Peach fruit waste is generated in large quantities as a result of the extraction of peach juice from the fruits during processing. During industrial processing, developed nations discard 35–40% of the waste produced by peaches [13]. Moreover, the quantity of produced peaches is influenced by maturity and processing. The peach waste includes some pieces of fruit, seeds, and skin.

According to a study of Chang et al. [74], peaches have a 30–36% dietary fiber content, of which 12% is soluble and 24% is insoluble on a dry weight basis. Dietary fiber concentrations in the pulp and peels, which were recovered as a byproduct of the extraction of peach juice, ranged from 31% to 36%, with 20–24% insoluble dietary fiber making up the majority. The soluble fiber fraction was larger than the soluble dietary fraction present in cereals and grains, ranging from 9% to 12% [75]. Pectin was discovered to be the predominant type of polysaccharides in the peach cell wall [76]. As a result, dietary fiber from peach fruit is suggested as a potential functional food element. Meats, baked goods, low-calorie beverages, and extruded products are among the suggested uses for peach dietary fiber as a functional additive [75].

4.2.4. Grape

Since about 67% of all grapes are used to make wine and other alcoholic beverages, grapes are a significant cash crop with a positive economic impact worldwide [77]. Approximately 5–9 million tons of grape pomace are produced annually as a result of this activity worldwide [78]. Cellulose and hemicellulose, together with trace levels of pectic materials, are present in grape pomace, which has the potential to be a valuable source of dietary fiber [79].

Grape pomace was investigated by Valiente et al. [80] as a potential source of dietary fiber. The total amount of dietary fiber found in the grape pomace was 78% (on a dry weight basis), of which 9.5% was soluble and the remaining 68% was insoluble. The study's findings showed that adding grape pomace, which is high in dietary fiber, to food products can be effective. According to Deng et al.'s [77] investigation of the pomace of several red and white varieties of dried grape skin, red wine grape pomace contains between 51% and 56% total dietary fiber, while white wine grape pomace has between 17% and 28% total dietary fiber. In a different investigation, it was discovered that the soluble dietary fiber content (10%) in the pomace of white grapes was lower than the insoluble dietary fiber (61%) [81]. Similar to this, Bender et al. [82] examined the effects of micronization on the dietary fiber from grape pomace (obtained from the red winemaking process) and found that 66% of the total dietary fiber contained 4% of soluble and 61% of insoluble fiber.

4.3. Vegetables

4.3.1. Tomato

Tomato is a crop that originated in South America and is regarded as valuable. One of the most significant vegetables grown globally, fresh tomatoes have an annual global production close to 242 million tons [37]. Tomato industrial byproduct production begins during transportation and continues through processing. According to estimations, 4 million tons of seeds, peel, and pomace are produced annually as byproducts, and their rapid decomposition and odor-producing microbial growth cause serious environmental issues. Around 50% (on a dry weight basis) of dietary fibers can be found in tomato pomace [83].

In a study conducted by Herrera et al. [84], the amount of dietary fiber extracted from dried tomato peels was 83% of the total amount, with a 10:1 ratio of soluble to insoluble dietary fibers. Silage can be used to preserve the large volumes of fresh tomato waste that the tomato processing industry generates [85]. When tomato pomace was extruded with corn semula and a starch component, Tadeu Pontes et al. [86] observed a doubling of the yield of soluble dietary fiber (up to 108%). The soluble fiber fractions and acid and neutral detergent fibers in tomato pomace were also assessed. These fibers were 9–12% hemicellulose, 12% cellulose, 37–44% neutral detergent, and 46–51% acid detergent fiber (all on a dry weight basis) [87].

4.3.2. Onion

Onion is the second most popular fresh vegetable harvested in the European Union after tomatoes [88]. The annual residues in onion production are estimated to be around 450 thousand tons, with the majority of these residues coming from the onion-processing industries in the Netherlands and Spain [89,90]. The onion skin, the outer two fleshy leaves, and the top and bottom trimmings of the bulb are the main byproducts of industrial processing of onions. Due to the nature of onion processing (removal of the fleshy leaves at the field or prior to loading into the peeler, trimming of the top and bottom of the bulb prior to skin removal, and obtaining onion skin by water/air removal), separate and reasonably well-defined fractions of vegetable parts can also be obtained from the processing facility [91].

Ample levels of dietary fibers are present in varying proportions in all onion layers. Jaime et al. [92] assessed the dietary fiber content of three distinct onion cultivars (skin and inner layers). Likewise, the skin of the "Grano de Oro" onion had the highest total dietary fiber content (63%), making it the highest among all other onion components, while the inner part had the lowest total dietary fiber level (12%). Moreover, the skin of the "Grano de Oro" variety of onion contained more insoluble dietary fiber (67%) than the inner component did. Benitez et al. [93] stabilized triturated onion wastes, liquid fractions, and solid leftovers through sterilization and pasteurization (residues). According to the study, industrial processing significantly affected the composition of bioactive chemicals. The best procedure to ensure the security of food containing dietary fiber was pasteurization. Moreover, this experiment showed that bagasse included substantial levels of nutritional fiber, ranging from 36% to 45% (on a dry weight basis).

4.3.3. Potato

High levels of bioactive chemicals, including dietary fiber-containing compounds, are present in potato wastes, particularly peel-based wastes [94]. Depending on the peeling technique, the amount of potato peel waste might range from 15% to 40% of the total product mass [95]. Since 40% to 45% of this residue's dry weight is made up of dietary fiber, it has been regarded as a valuable source of this substance. The composition of dietary fiber in potato peels and its hydration characteristics are affected by thermal processing [96]. Potato peels had a higher total non-starch polysaccharide content after extrusion heating and baking. However, the highest degree of soluble to insoluble ratio of non-starch polysaccharides was only associated with extrusion cooking. Processing caused the amount of "Klason" lignin to decrease, but it had no effect on the amount of uronic acids. The ability of potato peels to absorb water decreased after extrusion and baking [97,98].

Investigations have been performed into variations in the dietary fiber composition obtained from potato peels that have undergone extrusion heating and peeling. In steamed potato peels, extrusion cooking was linked to higher levels of lignin and total dietary fiber and lower levels of starch. During the extrusion of peels, the overall amount of dietary fiber remained unaltered even if the lignin concentration decreased. Both types of peels showed an increase in soluble non-starch polysaccharide after extrusion heating [96,99]. According to Ncobela et al. [100], the crude fiber content of potato peels ranges from 6.1% to 12.5% (on a dry weight basis). In line with previous studies, the range of dietary fiber in solid potato wastes was between 27% and 35% [101,102]. Overall, it can be mentioned that potato pulp, an underutilized waste or byproduct of the companies that produce potato starch, is a rich source of dietary fiber [103].

In general, an overview of the dietary fiber content in the processing wastes of selected commonly consumed cereals, fruits, and vegetables is provided in Table 1. As can be seen from the existing literature, most of the research studies took place on the extraction of dietary fiber from wastes; the characterization of those fibers and their potential applications is still at an early stage.

Table 1. Dietary fiber of some cereal, fruit, and vegetable derivatives (% dry matter).

Product	Waste Type	Total Dietary Fiber (TDF)	Insoluble Dietary Fiber (IDF)	Soluble Dietary Fiber (SDF)	Cellulose	Hemicellulose	Lignin	Pectin	References
Cereals									
Wheat	Seeds	11.6–17.0	10.2–14.7	1.4–2.3	-	-	-	-	[48]
Wheat	Seeds	10.2–15.7	7.2–11.4	1.9–2.9	-	-	-	-	[104]
Wheat	Seeds	9.2	-	-	-	-	-	-	[105]
Wheat	Bran	44.46	41.59	2.87	-	-	-	-	[106]
Wheat	Bran	44.0	41.1	2.9	-	-	-	-	[67]
Maize	Seeds	3.7–8.6	3.1–6.1	0.5–2.5	-	-	-	-	[107]
Maize	Seeds	13.1–19.6	11.6–16.0	1.5–3.6	-	-	-	-	[48]
Maize	Bran	87.87	87.47	0.40	-	-	-	-	[106]
Maize	Corncobs	90.0–93.0	-	0.8–2.0	35.0–39.0	43.0–46.0	3.0–6.0	-	[108]
Rice	Seeds	9.9	5.4	4.4	-	-	-	-	[109]
Rice	Seeds	2.7–4.9	1.9–4.2	0.6–1.1	-	-	-	-	[55]
Fruits									
Apple	Whole	86.0	63.0	22.0	-	-	-	6.0–8.0	[110,111]
Apple	Pomace	78.20–89.8	-	-	40.0–43.6	19.0–24.4	15.0–20.4	9.0–11.7	[112]
Apple	Pomace	89.0	70.0	19.0	44.0	24.0	20.0	7.0–23.0	[110,113]
Orange	Pulp	35.40–36.9	-	-	25.32	5.35	2.2–3.0	15.7–16.3	[112]
Peach	Pomace	31.0–36.0	-	-	28.7–30.0	18.6–20.0	5.35–6.0	20.5–23.8	[112]
Peach	Pomace/pit	54.0	36.0	19.0	31.0	22.0	27.0	-	[111,114]
Grape	Pomace	66.50–77.89	-	-	6.0–17.75	18.0–31.0	59.0–64.0	0.25–4.0	[112]
Grape	Pomace, stalk	74.0	64.0	11.0	38.0	14.0	33.0	32.0	[115]

Table 1. *Cont.*

Product	Waste Type	Total Dietary Fiber (TDF)	Insoluble Dietary Fiber (IDF)	Soluble Dietary Fiber (SDF)	Cellulose	Hemicellulose	Lignin	Pectin	References
				Vegetables					
Tomato	Pomace	44.90–59.03	-	-	19.02	12.0	36.0	7.55	[112]
Tomato	Pomace	59.0	-	-	9.0	5.0	3.0	-	[64,83]
Tomato	Whole	49.5	40.5	8.9	-	-	-	6.4–6.9	[111,116]
Onion	Skin/leaves	68.3	-	-	41.0	16.0	39.0	-	[92,117]
Potato	Pulp	84.3–91.3	-	-	17.0–21.7	14.0	2.6	2.2	[112]
Potato	Pulp/whole	-	-	-	4.0	14.0	0.4	10.0–12.0	[111]
Potato	Peel	73.0	20.0–53.0	10.0–20.0					[118,119]

5. Application of Dietary Fibers in Food Industry

Numerous industrial wastes and byproducts created during the food manufacturing process are not properly utilized, which causes significant environmental stress and pollution. Some of these can be used skillfully as a good source of dietary fiber, which will reduce pollution while adding value [120]. By affecting the rheological and thermal properties of the finished product, the enrichment of meals with dietary fibers is an efficient technique to improve nutritional and physiological aspects, as well as to boost functioning [121]. Dietary fiber has positive physiological effects and a number of beneficial qualities that can raise the standards of food products, such as eating quality, shelf stability of gums and pectin, and added technological value, especially for low-viscosity fibers [122]. The market has seen the introduction of numerous food and pharmaceutical items with dietary fiber added. Currently, dairy products, drinks, meat products, bread products, and food additives are the key areas of attention for dietary fiber research [52].

Higher fat content in ice creams and frozen yogurts has certain functions. Alginates, guar gums, and cellulose gels are examples of fiber ingredients that can be added in place of fat to provide viscosity, enhance emulsion, foam, freeze/thaw stability, control melting properties, lessen syneresis, encourage the formation of smaller ice crystals, and make extrusion easier [123]. Numerous studies have demonstrated that adding dietary fiber in varying amounts to yogurt enhances its nutritional content, as well as its texture, rheological properties, consistency, and general consumer acceptance [124]. Overall acceptance of yogurt that has been fortified with dietary fiber from lemon and orange has been positive [125]. According to Staffolo et al. [126], yogurt enhanced with 1.3% inulin (from wheat) and fibers (from apple) is a potential option for increasing fiber intake, and it has also grown in popularity with consumers. Hashim et al. [127] evaluated the effects of adding wheat bran (1.5%) and fortified date fiber (0%, 1.5%, 3.0%, and 4.5%) in different ratios to fresh yogurt. Yogurt enriched with fiber had a substantial impact on acidity when compared to control yogurt, and it was firmer and darker in color. However, yogurt that had been supplemented with 3% fiber also had comparable firmness, smoothness, sourness, sweetness, and acceptance overall. As a result, adding up to 3% date fiber to yogurt resulted in palatable yogurt with positive health effects [127].

Currently, there are many items made with flour that have been supplemented with dietary fiber on the market. Tudoric et al. [128] found that the biochemical composition, cooking qualities, and textural traits of both raw and cooked pasta were all affected by the addition of soluble and insoluble dietary fiber components. The addition of soluble dietary fiber also greatly lowers the release of glucose. The extrusion process for pasta is made easier thanks to several fibers from grains including oats, barley, soy, and rice bran that have anti-sticking properties. These fibers may also increase dough strength or extend the life of the cooked pasta on the steam table. Certain Asian noodle products that have gums added to them are firmer and simpler to rehydrate after cooking or soaking [129]. Typically, flour or flour-based goods such as biscuits, whole grain bread, steaming bread, and noodles are supplemented with dietary fibers [52].

Steamed bread and noodles can be made with wheat bran as a source of dietary fiber, and high-quality noodles can be made by including 5–10% dietary fiber [130]. Fiber additives have been shown to boost the water hydration values of flour when used in bread baking. According to Toma et al. [131], the bread prepared with the addition of potato peel instead of wheat bran has a greater water-holding capacity, total dietary fiber level, and vital mineral content. Consumer acceptance ratings were higher for cakes made with a 25% apple pomace and wheat flour blend. Along with other benefits, apple pomace fortification also offered a pleasing fruity flavor [60]. In a research study, 15% orange pulp and peel were suggested to be incorporated as an additional component in the production of biscuits [132]. Additionally, the incorporation of grape seed flour into waffles at a 10% concentration resulted in noticeable changes in the physical properties of the final product that could be acceptable to consumers [133]. Carotenoids and flavonoids, as well as dietary fiber, are thought to be abundant in pulp and peel. Additionally, it is advised to use defatted rice bran in place of wheat flour while making cookies. The cookies' sensory or physical qualities were unaffected by this swap, but their levels of minerals, dietary fiber, and protein were improved [134].

Since dietary fiber is deficient in meat, efforts are being undertaken to strengthen dietary fiber from diverse sources into a variety of meat products (meatballs, salami, and sausages) in order to improve the nutritional value. Today, it is more popular to add fiber to meat and/or meat products since it can effectively increase shelf-life, quality, and other processing features [135]. Dietary fibers made of pectins, cellulose, soy, wheat, maize, or rice isolates, as well as beet fiber, can be utilized to enhance the texture of meat products such as sausages and salami while also being suitable for making low-fat foods such as "dietetic hamburgers". Because dietary fibers can improve moisture, adding them to meat can give it a richer, juicier texture [136]. Due to their high-water retention and capacity to enhance texture and color, oat fiber can be employed as a suitable fat replacement in goods made from ground beef and pig [137]. Verma et al. [138] produced high-fiber functional chicken nuggets with low fat and low salt using a variety of fiber sources (pea hull flour, apple pulp, gram hull flour, and bottle gourd). In an effort to raise the overall quality of other meat products, researchers have tried to fortify them with dietary fiber. Supplementing meat emulsions with dietary fiber can increase emulsion stability and viscosity and reduce cooking loss [139]. Furthermore, dietary fiber may also be related to the rheological characteristics of meat emulsions [140].

In beverages and drinks, soluble fiber is mainly used to increase the viscosity and stability. Soluble fiber forms a gel-like substance when it comes into contact with water, which helps to thicken drinks and prevent settling or separation of ingredients. Other soluble fibers with possible applications include pectin, cellulose, and β-glucans [52]. Fruit and vegetable juices, quick drinks (breakfast drinks, milkshakes, sports drinks, iced tea, and wine), and other snack products all contain added oat fiber [123].

6. Application of Dietary Fibers in Nonfood Industry: The Case of Textiles

Textiles consume nearly 100 million tons of different fibers (primarily cotton, synthetic fibers, and cellulosic fibers from manmade materials). Over the past 20 years, the world's consumption of textile fibers has increased rapidly, with synthetic fibers covering the majority of the increase [141]. Today, a trend that has become increasingly popular is the search for more sustainable, alternative fibers, which are aimed at reducing the negative impact of textile production on the environment and the climate [142]. In addition to the use phase, the environmental impact of textile products is largely determined by the production phase. Specifically, the production of garments contributes approximately 80% of the total climate change impacts, mainly as a result of the use of fossil fuels in the production process. As part of this 80%, fiber production accounts for 16% of the impact of climate change. In the case of conventional cotton, the cultivation phase has the greatest impact on water scarcity (87 %) [141]. Therefore, some developments aim to break fossil-fuel dependency by substituting synthetic fibers with renewable alternatives, while others seek to reduce the use of water and land by replacing cotton with alternatives.

Fibers can be prepared in a variety of ways depending on the extraction techniques, including long continuous fibers, processed fibers, short-staple fibers, and powdered microfibers or nanometric fibers. Stems (bast fibers) were the most frequently reported source of natural fiber reinforcement extraction in earlier studies, whereas leaves were the least frequently recorded [143]. In order to create new cellulose fibers with mechanical qualities similar to those of traditional textile fibers, residues such as maize husks, rice, sorghum stalk and leaves, banana leaves, and others have been researched globally [144,145]. Exploiting different processing methods such as viscose, acetate, lyocell, and cupro to produce manmade cellulosic fibres from pulp with high cellulose content can further enhance the use of agro-waste in the textile industry and integrate the circular economy into the sector [146].

Technical lignins, which are cellulose byproducts, are gaining popularity as polymeric materials due to their widespread availability and biodegradability. These can take the place of synthetic fixed terms in engineering, stimulating and controlling the use of adhesives, fillers, and reinforcing agents, as well as in the textile industry as a textile fiber [147,148]. Additionally, the durability and recyclability of products including lignocellulosic fibers can be increased, contributing to the sustainable development of textile production [149]. A solution to the fashion industry's search for alternatives, as well as a route for the millions of farmers who burn their agricultural residues and release hazardous levels of emissions, can be established using fibers made from agricultural residues [150].

Among the cereals utilized for their plant waste, maize is typically presented as a cob and stem. Its primary uses include cellulose production [151–153] or as biocatalysts [154], reinforcement polymers [155], and enzymes for the textile industry [156]. Husks and husk bran from the production of rice are used for the production of enzymes [157] and cellulose nanocrystals [158], the adsorption of violet dyes [159], and the development of biodegradable composites [160] in the textile industry. Wheat is less common but offers a distinctive bran format for applications in the textile industry such as in composites [160] and enzyme production [161]. The incidence of additional materials, such as oat husks for the production of nanofibrillated cellulose, is also present in the cereal group [162].

For the production of nanofibers [163], nanocellulose [164], and dye adsorbent [165], orange peel exhibits the highest intensity of research with the pomace. Grape stems have been investigated for the creation of polymeric composites and the elimination of blue and brown textile colors [166,167]. Other fruits include papaya and mango for the production of enzymes for the textile industry [168], peach residues and waste peach branches for cellulose and cellulose nanofiber [145,169], and apple, avocado, and pomegranate for the removal of dyes [170–172]. Sweet potatoes and other tubers have composite potential as well [173]. Pecan nutshells are applied for the biosorption of cationic dyes [174].

7. Conclusions

This review paper demonstrates that substantial quantities of nonedible and edible parts of cereals, fruits, and vegetables are wasted throughout the entire agri-food supply chain. Insufficient pre- and post-harvest handling and processing operations are responsible for the generation of wastes. Despite this, the literature and available studies indicate that these wastes and/or byproducts contain a large number of bioactive compounds, including dietary fibers, which have a wide range of potential applications in the food and nonfood industries. An array of dietary fiber supplements can be prepared using cereal, fruit, and vegetable wastes and/or byproducts. However, for many economies, commercialization of agro-industrial food waste is still miles away despite the tremendous amount of research focused on its utilization in the development of new products. The majority of the studies are either conducted in research laboratories or on a pilot scale. In order for food waste-based biorefineries to succeed, optimized processes must be developed that take into consideration all technological and economic constraints. For large-scale implementation, it is, therefore, vital to conduct comprehensive research on both the potential recovery of high-value products and the environmental impact, including life cycle assessments and techno-economic analyses. Moreover, in order to move toward a circular economy, it is imperative to work toward the implementation of sustainable development goals across the globe and to ensure these goals through government interventions by drafting policies and laws that address ways in which food waste can be mitigated and/or utilized.

Author Contributions: Conceptualization, S.P. and I.R.; methodology, I.R. and S.P.; formal analysis, I.R and D.B.; investigation, I.R and S.P.; writing—original draft preparation, I.R. and S.P.; writing—review and editing, D.B. and G.P.; supervision, D.B.; project administration, G.P.; funding acquisition, G.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was co-funded by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship, and Innovation, under the call RESEARCH—CREATE—INNOVATE (project code: T2EDK-00084).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the research methodology, design, and writing of this review article.

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