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The Roles of Food Processing in Translation of Dietary Guidance for Whole Grains, Fruits, and Vegetables

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Abstract

The Dietary Guidelines for Americans (DGA) recommend the consumption of whole grains, fruits, and vegetables as part of a healthy diet. However, current consumption patterns suggest that most Americans are not meeting these recommendations. The challenge remains to align the DGA guidance with the food environment and consumers' expectations for product quality, availability, and affordability. Currently, processed foods play an increasingly important role in American diets. Often characterized as unhealthy, processed foods are contributors to both food and nutritional security. When the alignment of processing strategies with DGA principles exists, achieving DGA goals is more likely, regardless of processing level. In this review, select processing strategies for whole grains, fruits, and vegetables are described to show how DGA principles can guide processing efforts to create healthier products. Although whole grains, supported by industry-wide innovation and guidance, have had some success with consumers, improving intake of fruit and vegetable products remains a challenge. Closing consumption gaps requires new innovations and products aligned with consumer preferences and DGA principles.

INTRODUCTION

Every five years, the Dietary Guidelines for Americans (DGA) are updated to provide dietary recommendations with the ultimate goal of promoting optimal health, preventing chronic disease, and assisting in attaining and maintaining healthy weights for the American population (USDA & DHHS 2015). The latest DGA (2015–2020) provides guidance and recognizes the need for changes in food and beverage consumption by encouraging specific healthy eating patterns. Key recommendations include the need for consumers to follow "a healthy eating pattern that accounts for all foods and beverages within an appropriate calorie level" (USDA & DHHS 2015, p. 15). However, current recommendations for a healthy dietary pattern continue to include food group recommendations for consumption of fat-free or low-fat dairy, including milk, cheese, and/or fortified soy beverages; protein-rich foods, including seafood, lean meats and poultry, eggs, legumes, nuts, and soy products; whole grains (WGs) with the goal of making WGs half of the overall grain product consumption; fruits and vegetables (F&Vs), especially whole fruits and dark green, red, and orange vegetables; and oils that are predominantly rich in mono- and/or polyunsaturated fatty acids. Recommendations also highlight limiting saturated fats, sodium, and added sugars, with target levels of <10% of calories per day for added sugars and saturated fats and fewer than 2,300 mg of sodium per day.

With the stated goal of improving public health, translation of DGA principles remains dependent on alignment with consumer expectation for food product quality, availability, and affordability. In this regard, the DGA directly impact the food environment in the United States by providing guidance for food manufacturers on new product development or renovation of existing products that align with DGA recommendations and fit consumer dietary habits. This includes specific processed food categories. Despite the fact that most food products undergo some level of processing prior to reaching consumers, the consumer's general perception of food processing has continued to be negative (Dwyer et al. 2012).

Processing can be defined as "any deliberate change in a food occurring between the point of origin and availability for consumption" (Floros et al. 2010, p. 577). This involves the application of one or more operations, including but not limited to washing, grinding, mixing, cooling, storing, heating, freezing, filtering, fermenting, pressurizing, and packaging (Floros et al. 2010). Certain types of processed foods are justifiably categorized as being counter to the DGA recommendation because of their contribution of constituents that should be limited (i.e., saturated fat, added sugar, and sodium) (Poti et al. 2015). However, as a broad category, processed foods (particularly high-quality, nutrient-dense processed products) are generally believed to be a major component of healthy diets, as high-quality processed foods can close the gaps to the DGA nutrient recommendation by encouraging consumption of health-promoting micronutrients (e.g., fiber, vitamin D, folate) (Dwyer et al. 2012, Eicher-Miller et al. 2012, Weaver et al. 2014). Overall, the nutritional value of the food and not the level of processing appears to be the most important criteria in the development and selection of products to meet dietary guidance. With this in mind, strategic alignment of food processing with key components of the DGA can be critical to consumers' ability to meet DGA goals and thereby impact their health.

Although successful translation of dietary guidance to practice has been mixed, it is important to consider cases in which innovations in food science and nutrition have succeeded in enhancing adoption of DGA recommendations. In this regard, WG and F&V categories provide examples of two distinct scenarios, highlighting the importance of translational efforts that have focused on both nutritional and consumer aspects. Only ∼13% of US residents consume the recommended four-and-a-half cups of F&Vs per day (Moore et al. 2016). Significant efforts to increase public awareness of the benefits of F&V intake have been made; however, no significant change in product forms or consumer adoption has been observed over time (Rehm et al. 2016). In contrast, significant increases in WG consumption have been observed since 2001 (Mancino et al. 2008, Rehm et al. 2016). This has been associated with several factors, including the growth in processed products containing meaningful levels of WGs (**https://wholegrainscouncil.org/whole-grain-stamp/**).

With consumer demand and reliance on processed foods, continuous improvement is needed to ensure a high-quality and impactful food supply. This includes the development and marketing of products that align with DGA recommendations. Efforts underway rely on coordination among agriculture, nutrition, and food science disciplines to merge emerging nutrition research with the value chain. The purpose of this review is to describe progress made with WGs and F&Vs, with the intent of highlighting challenges and opportunities within each category. This includes an assessment of (*a*) where we are in addressing the consumption gaps for these food groups relative to the DGA recommendations for WGs and F&Vs, (*b*) the efforts underway to improve nutrient and bioactive content or functionality to better deliver benefits from popular WG and F&V products, and (*c*) how food technologies are being leveraged to extend WGs and F&Vs into broader consumer products that have the potential to align the consumer diet with DGA recommendations in these categories.

CURRENT DIETARY GUIDANCE AND THE IMPACT ON INTAKE OF WHOLE GRAINS AND FRUITS AND VEGETABLES

Fruits, Vegetables, and Whole Grains as Sources of Nutrients and in Chronic Disease Prevention

From 2005 to 2015, the DGA have highlighted the importance of selecting nutrient-dense foods to meet needs for essential vitamins and minerals as well as a balance of other health-protective compounds without a reference intake (i.e., phytochemicals). However, the term "nutrient-dense" remains somewhat loosely defined as "all vegetables, fruits, WGs, fat-free or low-fat milk and milk products, seafood, lean meats and poultry, eggs, beans and peas (legumes), and nuts and seeds that are prepared without added solid fats, added sugars, and sodium" (USDA & DHHS 2015, p. 12). It is important to note that this definition is not limited to fresh forms but also includes processed forms as long as they are delivering on key macro/micronutrient content in alignment with DGA principles.

F&Vs are well-recognized sources of key macronutrients, micronutrients, and health-promoting phytochemicals (**Table 1**). For example, fruits are a key dietary source of potassium and vitamin C, and vegetables broadly are considered a source of many essential nutrients, including potassium, vitamin A, C, K, E, and B_6, copper, magnesium, folate, iron, manganese, thiamin, niacin, and choline. Within the vegetable category, legumes in particular are well established as contributors of B vitamins, vitamin C, potassium, magnesium, phosphorus, and iron, and leafy vegetables contribute vitamin C, vitamin E, vitamin A (as provitamin A carotenoids), folate, iron, and calcium (USDA & DHHS 2015). It is also important to point out that F&Vs remain significant contributors to dietary fiber intake (Slavin & Lloyd 2012), and, as such, DGA recommendations further suggest that at least half of all fruits should be whole fruits (USDA & DHHS 2015). This specific point has led to some confusion by consumers about the specific role of processed products, such as 100% fruit juice, play in a healthy diet.

Beyond F&Vs, grains provide >14% of total daily calories, predominantly as starch, but also contribute to protein and lipid intake (Papanikolaou & Fulgoni 2017, Papanikolaou et al. 2017). The DGA identify WGs in particular for their contribution to dietary fiber, iron, zinc, manganese, folate, magnesium, copper, thiamin, niacin, vitamin B_6, phosphorus, selenium, riboflavin, and

Table 1 Fruits, vegetables, and whole grains as sources of key nutrients and bioactives

Nutrients	Fruits	Vegetables	Whole Grains
Macronutrients			
Carbohydrates	Yes	Yes	Yes
Fat	No	No	Yes
Protein	No	No	Yes
Total Energy	Yes	Yes	Yes
Micronutrients			
Vitamin A[a]	No	Yes	Yes
Vitamin D[a]	No	No	No
Vitamin E[a]	No	Yes	No
Vitamin C[a]	Yes	No	No
Vitamin K	No	Yes	No
Vitamin B_6	No	Yes	Yes
Potassium[a]	Yes	Yes	No
Choline[a]	No	Yes	No
Magnesium[a]	No	Yes	Yes
Calcium[a]	No	No	No
Dietary Fiber[a]	Yes	Yes	Yes
Iron[a]	No	Yes	Yes
Copper	No	Yes	Yes
Folate	No	Yes	Yes
Manganese	No	Yes	Yes
Thiamin	No	Yes	Yes
Niacin	No	Yes	Yes
Zinc	No	No	Yes
Selenium	No	No	Yes
Riboflavin	No	No	Yes
Phytochemicals			
Flavonoids	Yes	Yes	No
Carotenoids	Yes	Yes	Yes
Phenolic acids	No	No	Yes

[a]Nutrients represent key shortfall nutrients as indicated in the 2015–2020 Dietary Guidelines.

vitamin A (**Table 1**) (USDA & DHHS 2015). Specifically, grains provide greater than 20% of the intake of dietary fiber, folate, and iron and greater than 10% of calcium, magnesium, and vitamin A (Papanikolaou & Fulgoni 2017).

Recommendations for F&V and WG consumption have been guided by broader impacts of diet on human health, including the association of plant-based diets with a reduced risk of chronic and degenerative diseases such as cardiovascular disease, obesity, diabetes, age-related macular degeneration, neurocognitive diseases, and cancer (Aune et al. 2016, Berendsen et al. 2017, Boeing et al. 2012, Satija et al. 2017) (**Table 2**). These protective effects have been associated with both essential and nonessential nutrients (i.e., phytochemicals) (Cheng et al. 2017, Knekt et al. 2002, Marx et al. 2017). For example, F&Vs are well-recognized sources of biologically active carotenoids and flavonoids, which have biological activities consistent with disease prevention, including the ability to modify oxidative and inflammatory stress, endothelial function, xenobiotic metabolizing

Table 2 The roles fruits and vegetables and whole grain may have in prevention of chronic and degenerative diseases[a]

Chronic disease	Fruit and vegetables			Whole grains		
	Strength of evidence[b]	Study type	Source	Strength of evidence[b]	Study type	References
Cardiovascular disease	Convincing	Meta-analysis	Zhan et al. 2017	Convincing	Meta-analysis	Mellen et al. 2008
					Meta-analysis	Zong et al. 2016
Coronary heart disease	Convincing	Meta-analysis	Gan et al. 2015	Convincing	Meta-analysis	Aune et al. 2016
					Prospective cohort	Jensen et al. 2004
Hypertension	Convincing	Meta-analysis	Wu et al. 2016	ND	NA	NA
Stroke	Convincing	Meta-analysis	Hu et al. 2014	Insufficient	Prospective cohort	Johnsen et al. 2015
Asthma	Possible	Meta-analysis	Seyedrezazadeh et al. 2014	ND	NA	NA
Obesity	Possible	Meta-analysis	Schwingshackl et al. 2015	ND	NA	NA
Type II diabetes	Convincing	Meta-analysis	Wu et al. 2015	Convincing	Prospective cohort, systematic review	de Munter et al. 2007
		Critical review	Boeing et al. 2012[c]			
Chronic obstructive pulmonary disease	Possible	Prospective cohort	Kaluza et al. 2017	ND	NA	NA
Colon diseases	ND	NA	NA	Possible	Prospective cohort	Schatzkin et al. 2007
					Prospective cohort	Larsson et al. 2005
Cognitive impairment	Convincing	Meta-analysis	Jiang et al. 2017[d]	ND	NA	NA
Osteoporosis	Possible	Prospective cohort	McTiernan et al. 2009	ND	NA	NA
		Longitudinal cohort	Tucker et al. 1999			
Eye disease	Possible	Cross-sectional study	Moeller et al. 2004[e]	Possible	Cross-sectional study	Moeller et al. 2004
		Case control	Seddon et al. 1994			
Arthritis	Possible	Prospective cohort	Cerhan et al. 2003	ND	NA	NA

[a]Chart displays select data (primarily meta-analyses). Two studies are listed in some cases to provide further support for the determined level/strength of evidence.

[b]The strength of evidence for disease prevention was determined based on the type of article (e.g., meta-analysis > prospective cohort/case control > cross-sectional study), the study design and confidence in which conclusions were drawn, and article findings (i.e., author conclusions) for the role of fruits and vegetables in decreasing risk of the specified disease.

[c]There is insufficient evidence to support consumption of fruits and vegetables for the reduced risk of type II diabetes independent of weight loss associated with fruit and vegetable consumption.

[d]Inverse relationship was found among participants with a mean age of 65 years or older.

[e]Fruits, but not vegetables, were found to have an inverse relationship with nuclear lens opacities.

Abbreviations: NA, not applicable; ND, not determined.

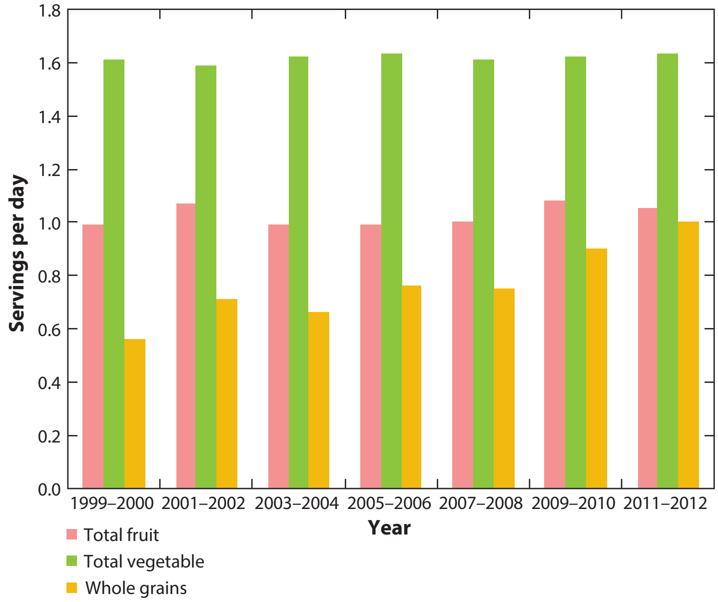

Figure 1

Changes in fruit (*pink*), vegetable (*green*), and whole-grain (*gold*) consumption as documented in "Dietary Intake Among Adults, 1999-2012" (Adapted from Rehm et al. 2016). Data obtained from the National Health and Nutrition Examination Studies (NHANES) analysis from 1999–2012.

systems, and nutrient bioavailability and utilization (Eisenhauer et al. 2017, Kaulmann & Bohn 2014, Shahidi & Ambigaipalan 2015, Woodside et al. 2015). However, phytochemicals do not yet have established dietary reference intake (DRI) values and remain dependent on adherence to food-based guidance for F&Vs and WGs as a primary means for consumers to achieve relevant or beneficial effects.

Consumption Gaps for Fruits, Vegetables, and Whole Grains

Despite significant policy and communication efforts, only a small fraction of Americans are actually achieving the DGA recommendation (Schwartz et al. 2017) (**Figure 1**). The National Health and Nutrition Examination Survey (NHANES) data from 2007–2010 reported that less than 24% of the American population met current guidelines for fruit consumption and less than 13% for vegetable consumption (USDA & DHHS 2015). Primary product forms have remained constant over the years for F&Vs and include fresh, canned, frozen, dried, and 100% juice. Interestingly, although total fruit consumption, excluding fruit juice, subtly increased by 7%, there was a 21% reduction in 100% fruit juice consumption from 2004–2014 (PBHF 2015). The increased negative perception of the sugar content of 100% juice along with the tentative associations with weight gain may have influenced consumption patterns (Byrd-Bredbenner et al. 2017). A similar decline in 100% fruit juice was reported by Rehm et al. (2016). This is despite the fact that a recent meta-analysis of 100% juice consumption found no association with weight gain in children 7–18 years (Auerbach et al. 2017) and that 100% fruit juice consumption has been associated with improved overall diet quality (O'Neil et al. 2012).

Policy and communication efforts have been one strategy to address this need but have shown mixed results. To increase awareness and promote consumption of F&Vs, the five-a-day national campaign was launched in 1991. Despite significant efforts and funding, F&V consumption was not significantly impacted (Casagrande et al. 2007). However, some successes were observed with programs targeting specific food environments. For example, the Healthy, Hunger-Free Kids Act and the National School Lunch and Breakfast programs have been responsible for the recent increase in whole-fruit consumption by children (12% per year, 2003–2010) (Kim et al. 2014). Success in this case was likely a result of increased availability of fruit products for children at school rather than simply encouraging them to consume more or increasing nutrition awareness. Furthermore, these programs did not directly encourage innovation for new fruit or vegetable products that meet DGA goals.

In contrast to the general lack of progress with F&Vs, the recommendations for increased intake of WG products have seen more success. From 2003 to 2013 average consumption of WG products has increased by 50% in the US population (Rehm et al. 2016). This relative success is due, in part, to increased consumer awareness and an increasing amount of new WG food products that deliver nutrient-dense WG components (Mancino et al. 2008). This alignment between DGA recommendations and WG-based consumer products was achieved, in part, through collaborative efforts between industry and academia. The Whole Grain Council and the American Association of Cereal Chemistry International led by establishing clear standards and definitions for WGs and WG foods (a minimum of 8 g of WGs per 30 g serving) (AACCI 2018; **https://wholegrainscouncil.org/**). Such guidance provided a structure for the food industry to align consumer expectation with the DGA recommendations. This includes diversification of WG food options from staples such as yeast breads and rolls and crackers to complex products, including frozen meals, soups, and meat substitutes (Albertson et al. 2016). Along with diversifying WG products, food manufacturers also strive to increase their popularity and availability. A clear example of this shift is the fact that whole-wheat bread sales surpassed those of white-wheat products for the first time in 2010 (Rowe et al. 2011).

When translating dietary guidance into practice, a fundamental understanding of the alignment of products with consumer preferences is key. One fundamental reason for this difference in these two food categories may lie in the perception of processed foods. Processed foods are a critical part of everyday lives, making up more than 71% of the total dietary intake in the United States today (Poti et al. 2015). Although all grain products require some level of processing prior to human consumption, fresh and minimally processed fruits and vegetables are the most commonly recommended forms for consumers (USDA & DHHS 2015). This makes for an interesting distinction, as processed foods are often broadly characterized as unhealthy and criticized for their lack of nutrient density and misalignment with the spirit of the DGA (Huth et al. 2013). However, many processed food forms are best aligned with consumer preferences for convenience, affordability, and taste, which drive purchase and consumption choices (IFIC 2018, Weaver et al. 2014).

Better alignment between processed food forms and dietary guidance is needed. However, the contribution of processed foods to overall nutrient intake in the United States is already significant. Eicher-Miller et al. (2012) utilized the International Food Information Council (IFIC) definitions for levels of processing and estimated contribution of processed foods to essential macro- and micronutrient intakes based on NHANES (2003–2008) records. Results suggest that foods across all levels of processing contribute to intake of key nutrients and that nutrient density and not actual level of processing should be the key determinant in the selection of products for their alignment with the DGA principles (**Figure 2**). In a follow-up assessment, Eicher-Miller et al. (2015) reported that in children 66%–84% of total daily energy, saturated fat, cholesterol, fiber, total sugar, added sugars, calcium, vitamin D, potassium, and sodium intake are contributed by one of the five categories of processed foods. Considering this and the general notion that processed foods make significant contributions to overall dietary intake of Americans (Poti et al. 2015, Weaver et al. 2014), opportunities for improvement of the quality of processed fruits, vegetables,

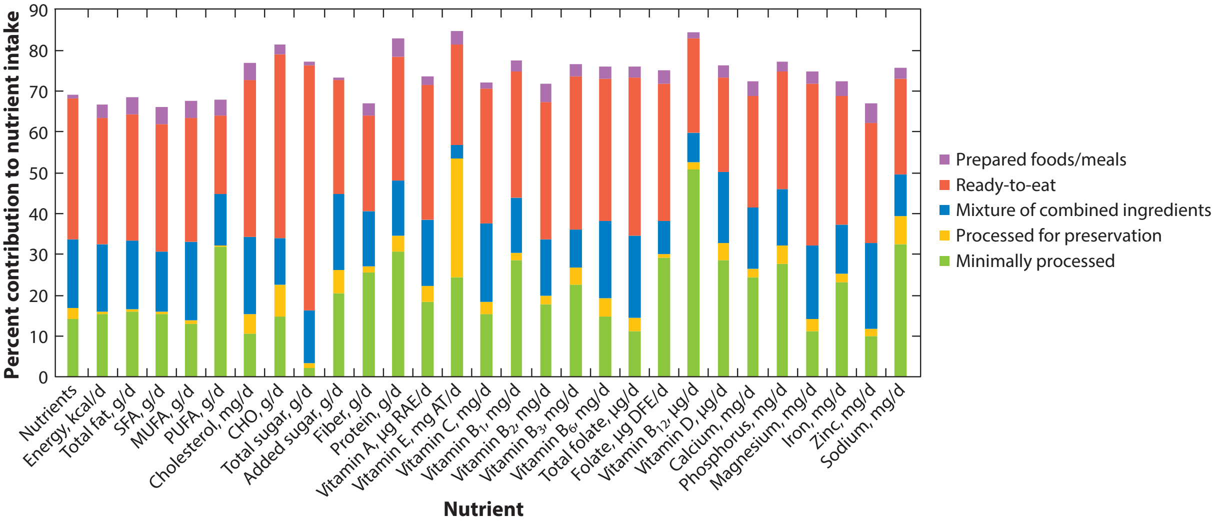

Figure 2

Contribution of processed foods to nutrient intake in the American population (NHANES 2003–2008, >2 years old, IFIC and Food and Nutrition Database for Dietary Studies). Level of food processing is defined using the International Food Information Council (IFIC) definitions for processed foods: minimally processed, foods that require processing or production (*green*); processed for preservation, foods processed to help preserve and enhance nutrients and freshness of foods at their peak (*yellow*); mixture of combined ingredients, foods that combine ingredients such as sweeteners, spices, oils, flavors, colors, and preservatives to improve safety and taste and/or add visual appeal—does not include ready-to-eat (RTE) foods (*blue*); RTE, foods needing minimal or no preparation (*red*); and prepared foods/meals, foods packaged to stay fresh and save time (*purple*). Percentages in figure do not add to 100%, as these data do not account for food consumed at restaurants/dining halls or unprocessed foods. Derived from data reported by Eicher-Miller et al. (2012). Abbreviations: CHO, carbohydrates; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids; SFA, saturated fatty acids.

and WG foods are paramount. The alignment of food processing with the nutritional/health needs of the US population could generate a diverse product space for consumers to meet guidance in categories such as WGs and F&Vs. Alignment such as this is critical considering the significant contribution of processed foods to American diets and the opportunity of improved products to impact health.

ROLE OF FOOD AND INGREDIENT PROCESSING IN DELIVERY OF WHOLE GRAIN TO CONSUMERS

The relative success of implementing DGA recommendations for WG foods is a result of several factors, including (*a*) creation of standards and product guidance, (*b*) synergistic efforts of agricultural systems and food technologies, (*c*) diversification of the WG product space, and (*d*) successful public education on the role of WGs in healthy diets.

Whole-Grain Foods and the Technology Applied to Their Generation

WGs as an important component of a nutrient-dense diet are believed to benefit gut health and to reduce risks of cardiovascular diseases and type II diabetes (Chanson-Rolle et al. 2015, Martínez et al. 2013, Marventano et al. 2017, Zong et al. 2016). WG foods are typically formulated from refined and recombined grain fractions designed to deliver the key botanical components of intact

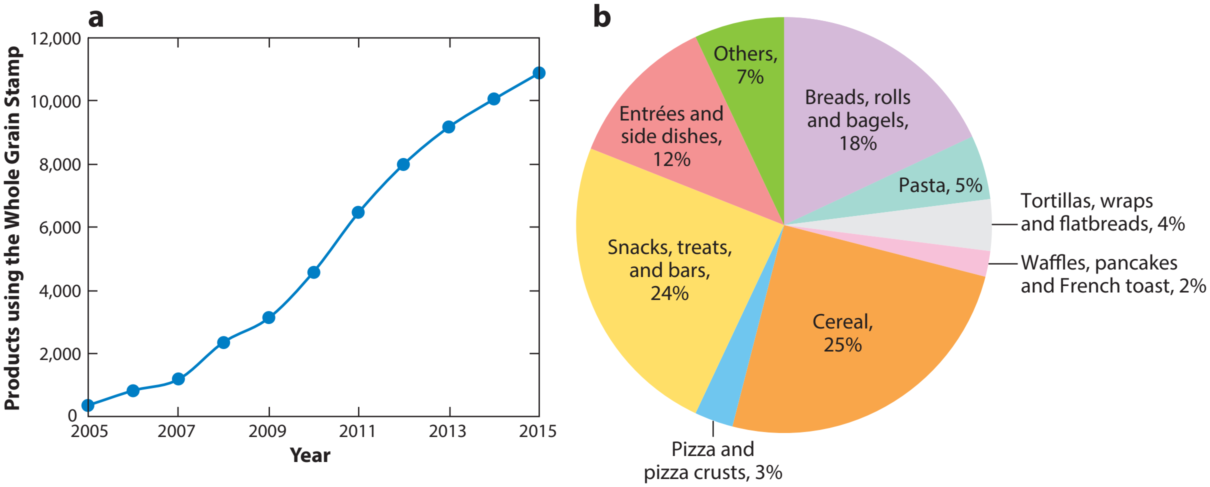

Figure 3

Availability of whole-grain food products in the market. (*a*) Products using the Whole Grain Stamp have increased significantly between 2005 and 2015. (*b*) As of May 2018, more than 12,000 products are whole-grain stamped in 58 countries, covering a wide range of grain-based foods. Data obtained from Whole Grains Council website (**https://wholegrainscouncil.org/whole-grain-stamp/**).

grain, including the starchy endosperm, germ, and bran "in the same relative proportions as they exist in the intact caryopsis" (AACCI 2018). WG foods are a superior dietary source of grain-derived fiber, micronutrients, and phytochemicals compared to their refined grain (RG) counterparts (Frølich et al. 2013). Therefore, enhancing consumption of WG products is essential to leverage public diet quality.

Rehm et al. (2016) reported that daily intake of WG-based foods almost doubled from 0.56 to 1.0 servings between 1999 and 2012. This is despite the fact that consumer acceptance of WG products is not without its challenges. Inclusion of bran/germ components is often accompanied with some degree of alterations in physical and nutritive attributes of traditional grain-based products (e.g., breads and ready-to-eat cereals) as well as their sensory perceptions (Heinio et al. 2016). Overcoming these challenges has driven diversification of WG product forms (**Figure 3**), provided consumers with alternatives to achieve WG servings, and accelerated the growing implementation of the DGA WG recommendation. This has required some alignment between agricultural and food processing systems to optimize high nutritional/functional values, product quality, and sensory characteristics.

Impact of Whole-Grain Reformulation on Nutritional Quality of Grain Products

Nutritional comparisons of WG and RG counterparts highlight some of the challenges associated with this conversion. The USDA National Nutrient Database for Standard Reference reports that WG foods have starch and protein contents similar to those of RG products (**Table 3**). WG wheat bread, for example, has a carbohydrate content close to its RG counterpart [475 versus 427 mg/g fresh weight (FW)] (USDA 2018). Most notably, WG food products contain higher contents of dietary fiber (e.g., cellulose, hemicellulose, lignins, arabinoxylans, and β-glucans) compared to RG counterparts such as wheat bread (60 versus 40 mg/g FW) and wheat pasta (92 versus 32 mg/g FW). This is generally considered a positive factor for gastrointestinal health (Simpson & Campbell 2015).

Table 3 Impacts of the whole grain strategy on nutritional qualities of wheat-based food materials[a]

Nutrients	Flour		Bread		Pasta	
	WG	RG	WG	RG	WG	RG
Macronutrients[b]						
Protein (g)	13	12	4.0	3.1	7.9	7.4
Fat (g)	2.5	1.7	1.1	1.3	1.7	0.9
Carbohydrate (g)	72.0	72.5	13.7	13.8	41.6	42.3
Dietary fiber (g)	10.7	2.4	1.9	1.2	5.2	1.8
Minerals[b]						
Calcium (mg)	34	15	52	36	16.2	11.8
Iron (mg)	3.6	0.9	0.8	1.0	2.1	0.7
Magnesium (mg)	137	25	24	12	72	30
Phosphorus (mg)	357	97	68	37	194	107
Potassium (mg)	363	100	81	41	246	126
Sodium (mg)	2	2	146	137	3	3
Zinc (mg)	2.6	0.9	0.6	0.3	1.7	0.8
Vitamins[b]						
Thiamin (μg)	502	80	126	119	231	51
Riboflavin (μg)	165	60	53	73	123	34.3
Niacin (mg)	5.0	1	1.4	1.6	4.9	1.0
Vitamin B_6 (mg)	0.4	0.04	0.07	0.03	0.2	0.08
Folate (μg)	44	33	13	29	39	10
Vitamin E (mg)	0.7	0.4	0.9	0.06	0.3	0.06
Vitamin K (μg)	1.9	0.3	2.5	1.4	0.8	0.06
Phytochemicals[c]						
Ferulic acid (mg)	65.7–71.4	4.9–6.0	12.6–15.5	1.9–2.1	0.3–15.5	3.1
Total phenolics (mg)	75.2–80.9	5.6–7.2	13.1–21.9	2.0–3.4	43.8–86.7	3.1–40.7
Sitosterol (mg)	40.5–44.0	19.0–43.6	13.6	7.7–9.9	4.7	2.9–3.2
Total phytosterols (mg)	70.0–74.4	28.0–68.7	24.9	13.0–17.3	8.3	4.7–5.4
Choline (mg)	3.7–16.9	3.9–5.7	4.4–6.2	1.8–2.4	6.0–14.1	4.0–4.8
Total Betaine (mg)	50.7–79.2	14.1–39.8	14.5–24.2	5.6–9.2	40.3–72.9	35.6–40.0

[a]Nutrition contents of wheat flour, bread, pasta, and crackers were reported based on the recommended serving sizes of 100 g, 1 slice (32 g WG versus 29 g RG), and 56.7 g, respectively.
[b]Values were extracted from Food Composition Database of United States Department of Agriculture (**https://ndb.nal.usda.gov/ndb/**). The USDA report numbers were 20080, 20129, 18075, 18064, 20124, and 20420.
[c]Values were derived from previous reports by Beleggia et al. (2011), Bruce et al. (2010), Hirawan et al. (2010), Lu et al. (2017), Normen et al. (2002), Piironen et al. (2002), and Ross et al. (2014).
Abbreviations: RG, refined grain; WG, whole grain.

In addition to increased dietary fiber, formulation with WG provides higher levels of micronutrients relative to RG foods (**Table 3**). For examples, whole-wheat flour has higher mineral contents, including calcium (1.6 versus 1.3 mg/g FW), magnesium (0.8 versus 0.4 mg/g FW), and iron (36 versus 25 μg/g FW), than refined wheat flour (USDA 2018). This supports the notion that WGs can enhance nutrient density of a diverse array of grain-based foods. However, it should be noted that higher micronutrient levels in WGs do not necessarily translate to higher bioavailability compared to refined and fortified products. Other factors such as the food matrix also actively interfere with the absorption processes for certain nutrients. For instance, Leklem et al. (1980) observe that humans fed a whole-wheat-bread-based diet have modestly lower vitamin B_6 levels in plasma than those fed a refined-wheat-bread diet after a six-day clinical trial (42.9 ± 13.2 versus 46.5 ± 11.2 nM), even though the whole wheat had significantly higher levels of vitamin B_6 compared to refined wheat (1.20 ± 0.06 versus 0.35 ± 0.04 mg/day). This inconsistency between dietary content and bioavailability is largely attributed to food matrix factors, as most vitamin B_6 is believed to be bound in WG wheat (Leklem et al. 1980).

Bran and germ fractions of WGs are rich sources of many dietary bioactive compounds, leading to WG products with phytochemical contents superior to their RG counterparts. Whole-wheat bread, for instance, contains 450.9–754.5 μg/g FW of total phenolic compounds (Lu et al. 2015) and ∼0.86 mg/g FW of total phytosterols (Normen et al. 2002, Piironen et al. 2002). These values are not only significantly higher than those of the refined wheat breads (63.4–106.2 μg/g FW of total phenolics and 0.41–0.54 mg/g FW of total phytosterols) (Lu et al. 2015, Normen et al. 2002, Piironen et al. 2002) but also close to other phytochemical-rich foods, including many fruits (1.8–7.5 mg/g dry weight of total phenolics) and nuts (0.19–2.55 mg/g of total phytosterols) (Wang et al. 2018, Wojdylo et al. 2016). Considering the contents of dietary fiber, micronutrients, and phytochemicals, it is reasonable to understand the potential impact on public health through enhancement of WG food consumption (Abuajah et al. 2015, Gylling et al. 2014, Li & Hagerman 2013).

Impact of Whole-Grain Components on Product Quality and Consumer Acceptance

Although public education on WG health benefits can enhance acceptance of WG products (Neo & Brownlee 2017), sensory expectation still dominates consumer choice (Teuber et al. 2016). As stated previously, simple translation of product formulations from RGs to WGs is not without complications. Product performance and quality is a challenge with traditional processing systems, as interactions between aforementioned nutrients and food matrices result in alterations of product appearance, taste, and texture. Overcoming these challenges to deliver high-quality WG foods was and has remained a major hurdle to the successful adoption of WG products. Improving both agricultural systems and food processing methods to deliver quality consumer products is a central strategy for fostering WG-rich diets.

Fiber-rich bran, which could account for 10%–14% of the whole grain (Fardet 2010), can unfavorably affect product and sensory attributes of baked products. Specifically, fibers from wheat bran can inhibit gluten structure and reduce gluten yield of refined wheat dough (Cai et al. 2014, Chaplin 2003). Such alterations affect starch gelatinization and starch–gluten network development, resulting in prolonged dough development time and reduced dough stability (Hemdane et al. 2016, Noort et al. 2010). This can compromise baking performance of wheat-based products, leading to reduced bread-loaf volume as well as lower consistency in bread and biscuit (Stanyon & Costello 1990, Wang et al. 2002). In addition, bran has stronger water-absorbing tendencies than refined flour. The addition of bran can therefore increase meal water consumption and chewiness of grain-based products (Stanyon & Costello 1990). These bran-induced changes partially explain the historic reduction in overall consumer acceptance when dietary fiber is formulated with wheat breads (Wang et al. 2002).

Phytochemical components can also affect product performance and sensory attributes of WG products (**Table 4**). Carotenoids and phenolics from bran and germ fractions are associated with increased darkness of grain-based foods (Yang et al. 2014). These components may reduce acceptance of WG breads (Bakke & Vickers 2007), especially as young consumers (such as children at grades K-6) prefer lighter products (Burgess-Champoux et al. 2006). In addition, phenolics and sterols are reported to affect bread texture through disruption of the starch–gluten matrices. The former is believed to deleteriously affect gluten network development by enhancing

Table 4 Reported impacts of whole grain fibers and phytochemicals on the sensory perception of grain-based products[a]

Sensory perception	Impacts	Active grain ingredients
Appearance	Increased darkness of grain products	Carotenoids and phenolics
Texture	Decreased bread volume	Dietary fiber
	Decreased cohesiveness	Dietary fiber
	Increased chewiness	Dietary fiber
	Increased crispness and acoustic performance	Phytosterols
Taste	Bitterness, grain-like, and sourness of bread crumb	Free and bound phenolics
	Astringency, grain-like and sour of crackers	Bound phenolics

[a]Summarized based on previous reports from Wang et al. (2002), Cai et al. (2014), Noort et al. (2010), Stanyon & Costello (1990), Yang et al. (2014), Bakke & Vickers (2007), Jakubczyk et al. (2015), Challacombe et al. (2012) and Neo & Brownlee (2017).

fiber–gluten interactions (Noort et al. 2010), whereas the latter can positively enhance the crispiness and acoustic performance of extruded crispy bread by altering water activity (Jakubczyk et al. 2015). More importantly, a recent study shows that both free and bound phenolics are actively involved in shaping the bitterness, grain-like attributes, and sourness of bread crumb, whereas the bound phenolics of crackers are major players in modulating the astringency and grain-like and sour attributes (Challacombe et al. 2012).

Roles of Processing Techniques in Delivering Nutritious Whole-Grain Products

With obvious challenges in transitioning from RGs to WGs in multiple product formats, it is important to consider several strategies employed by the industry to deliver products with WG nutrition but function that matches consumer expectations of typical RG counterparts. From crop genetics and agronomic factors to modification of traditional formulations and processing techniques, extensive research has been conducted by academic and industrial groups through the years to optimize each step of WG food production (**Figure 4**). Many of these approaches have been previously reviewed for WG products such as oats (Decker et al. 2014) and wheat (Dewettinck et al. 2008). To highlight some of the success that has promoted alignment of WG products with the DGA recommendations, this review focuses on WG wheat breads, which represent almost 20% of the total products using WG stamps (**Figure 3**).

Efforts to optimize performance of whole-grain wheat in breads. To fulfill consumers' expectations for optimized product performance, breeding, milling, and bioprocessing strategies are constantly used to improve macronutrient functionalities, especially in the development of starch–gluten network during bread baking, for presenting bread products with superior qualities (e.g., finer texture, larger loaf volume). The same three strategies are also applied to ensure the delivery of WG nutritive benefits by either elevating contents of select health-promoting bioactive components or improving the bioavailability of targeted phytochemicals.

Breeding. Breeding is the front line for improvement of nutrient density and product performance of WG wheat breads. As low product quality and sensory perception of whole-wheat breads are largely attributed to impaired networks of the starch–gluten matrix (Hemdane et al. 2016, Noort et al. 2010), trait-based hybridization has been used to select bread wheat genotypes

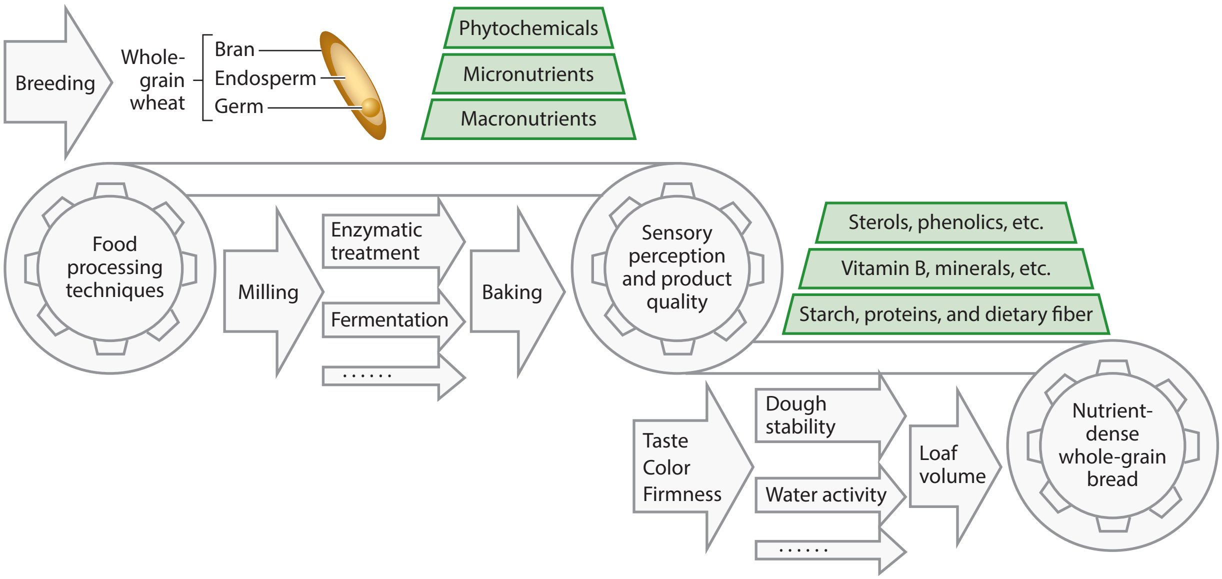

Figure 4

Overview of breeding, food processing, and product formulation efforts that deliver nutrient-dense whole-grain (WG) wheat breads. Extensive research has been performed to optimize phytochemical (e.g., sterols, phenolics), micronutrient (e.g., vitamins, minerals), and macronutrient (e.g., starch, protein) contents of WG breads. WG bread production is commonly optimized to align with consumer expectation for product quality, including taste and texture.

with high total protein content, high wet gluten contents, and a high gluten index for better rheological properties. Such functional breeding programs have been assisted and augmented by genomic approaches. Deng et al. (2015) identified 56–77 gluten/rheology-relevant quantitative trait loci from 19 different wheat chromosomes. Although 20–34 of the loci are ascribed to the phenotypic variance (>10%), the others are likely associated with difficult-to-phenotype traits. Simultaneous expression of gluten and rheology relevant genes can therefore be achieved through a coupled-genomic-selection/trait-based hybridization process. Optimizing compositions of dietary fiber is another target for the breeding of WG bread wheat. An early study shows that genetic factors contribute 39%–71% of the total variance for bran arabinoxylan (a soluble fiber) levels (Shewry et al. 2010). Although arabinoxylan synthesis by wheat is subjected to environmental and agronomic influence, the high heritability among bread wheat cultivars indicates a potential to foster wheat cultivars with elevated dietary fiber contents.

Breeding is also used to modulate content and activity of beneficial WG phytochemicals. After analyzing phytochemical contents from 26 wheat cultivars, Shewry et al. (2010) discovered strong genotypic contributions to the phenotypic variance of total tocopherols (77%) and total phytosterol (57%) contents. Taranto et al. (2012) observe that polyphenol oxidase activity is associated with four different alleles. Although these phenotypic variances are subjected to environmental influence (Shewry et al. 2010, Taranto et al. 2012), the inheritable traits make it possible to select WG wheat cultivars with varied phytochemical contents and browning indexes through a coupled-genomic-selection/trait-based hybridization process. This facilitates selection of wheat genotypes that optimally balance phytochemical content with appropriate color properties for baking applications.

Milling. Milling of grain into flour is a critical process with functional and nutritional consequences. For the most part, WG products are produced from milled grain and RG that are subsequently recombined (flour, bran, and germ) into a WG flour. As described previously, incorporation of bran has a negative impact on bread texture, color, and taste. Germ incorporation similarly impacts quality through the incorporation of oxidatively unstable lipids (Majzoobi et al. 2012). Milling conditions and the extent of recombination can be optimized to manage many of these negative factors. Delcour et al. (2012) reported a fractionation procedure that removes outer pericarp and bran crease materials of wheat grains by pearling and milling, respectively. This fractionation provides the resulting WG wheat flour with improved product performance (e.g., finer texture, larger loaf volume, less bitterness) in final bread products while providing comparable nutritive values to intact WG products. Particle size is also a critical factor to modulate bran functionality. Cai et al. (2014) reported that bran with smaller particle sizes (105–420 μm sieves) significantly enhanced water absorption for dough and crumb firmness for bread. These observations were attributed to the enhanced starch retrogradation, as smaller bran particles have larger surface area for water–bran fiber interactions (Cai et al. 2014, Chaplin 2003). However, it should be noted that the impact of bran particle size is subjected to other compositions in the whole-wheat matrix such as gluten protein content and quality (Hemdane et al. 2016). Higher gluten protein content and/or better protein quality can sometimes counteract the deleterious effects of fiber-rich bran.

Advances in milling technology have also allowed fine-tuning of phytochemical levels in whole-wheat ingredients. Early research developed biochemical markers to quantify wheat grain tissues: outer pericarp (ferulic acid trimer), intermediate layer (alkylresorcinols), aleurone cell walls (*p* coumaric acid), aleurone cell contents (phytic acid), endosperm (starch), and germ (wheat germ agglutinin) (Hemery et al. 2009). Such techniques allow for rapid estimation of phytochemical contents of specific milled fractions so that wheat flour can be properly formulated to address nutritional and sensory requirements for various bread products. In addition, a coupled ultrafine grinding/electrostatic separation method has been designed to enrich phenolic content from wheat bran (Delcour et al. 2012). The resulting fraction has higher total phenolic content and maintains higher bioaccessibility while containing only one-third of the initial bran weight.

Bioprocessing. Enzymatic treatments and fermentation have been shown to positively affect macronutrient performance in WGs in bread making. Addition of α-amylase is reported to enhance dough development and the proofing process, leading to increased loaf volume (Penella et al. 2008). Xylanase treatment can hydrolyze arabinoxylan (dietary fiber) to smaller oligosaccharides, resulting in higher expansion capacity and better bread firmness (Yang et al. 2014). Lipoxygenase treatment is found to positively affect loaf volume (Hemdane et al. 2016). On the one hand, lipoxygenases prevent gluten network development from deleterious interference by oxidizing methoxyhydroquinone and glutathione. On the other hand, it increases nonpolar/polar lipid ratio via the oxidations of polyunsaturated fatty acids. Increments in the ratio are believed to enhance the stabilizing effects of liquid lamellae on gas bubbles during bread baking. Fermentation is believed to increase gluten solubility in dough, consequently stimulating network development of the starch–gluten matrix (Hemdane et al. 2016).

Enzymatic treatments can also modulate phytochemical functionality in whole-wheat bread and thus improve consumer acceptance. Papain and glucose oxidase are used to fine-tune browning index of whole-wheat bread through modulating oxidations of phenolics and carotenoids (Yang et al. 2014). Similar enzyme treatment can enhance phenolic bioavailability and anti-inflammatory activity in humans, suggesting that improvements are possible in both processing and nutritional functionality through bioprocessing (Anson et al. 2009).

Remaining Challenges and Future Possibilities for Whole Grains

Although consumption of WGs has steadily increased in the past 10 years, maximizing health benefits from the current consumption levels of WG foods remains a critical issue. For example, WG foods have been documented to have relatively low bioavailability for many health-promoting compounds, including vitamin B_6, choline (Hedemann et al. 2015, Leklem et al. 1980), and phenolics, that remain inherently bound to the bran fraction. Improving absorption of micronutrients and phytochemicals is thus the subject of intense investigation (Delcour et al. 2012, Li et al. 2016).

In addition to ongoing processing/health research, continuous development of new WG foods (beverages, snacks, and fermented products) remains promising. This research goes hand in hand with constant consumer research to fulfill the expectations for beneficial nutritive contents as well as superior product performance (Heinio et al. 2008, Stanyon & Costello 1990, Teuber et al. 2016). Interactions between endogenous bioactives and sensory qualities (Jiang & Peterson 2010) appear most critical to manage through optimized processing techniques. Extending this to better understand storage requirements for WG foods (Jensen et al. 2011) is also critical for the continued success of WG foods.

POTENTIAL FOR FOOD PROCESSING TO ENHANCE FRUIT AND VEGETABLE DELIVERY TO CONSUMERS

Although many innovations have been leveraged to enable WG consumption, a disconnect still exists with F&V consumption. Although some consensus has been achieved to define nutritional and product targets that meet WG standards, this has been far more challenging for the F&V space. The priorities for F&V processing are safety (via inactivation of microorganisms) and quality (inactivation of enzymes, color loss). Product quality may consider residual content of vitamin C, often the nutrient most vulnerable to degradation (Rickman et al. 2007a). However, nutrition has not traditionally been the major driving factor for optimizing F&V processing or product innovation. Innovations in processed F&V products may be applied to optimize nutrition, yet challenges exist in making these products accessible and acceptable to consumers. In addition to having high nutrient quality, these food products must be economically optimized and have favorable sensory characteristics, and consumers should also be aware of how these processed F&V products translate to actual fruit or vegetable servings. The following sections highlight major F&V product forms, their associated technologies and effects on quality, and current obstacles that limit F&V consumption in the United States.

Fruit and Vegetable Technologies and the Product Landscape

To better align DGA recommendations with food innovation strategies, academic researchers and industrial manufacturers have applied various technologies to diversify F&V forms, including fresh, frozen, dried, canned, and thermally processed products as well as F&V juice products. However, compared to WG foods, limited progress has been made to successfully translate F&V dietary guidance to practice. Major challenges persist due to, in part, (*a*) limited diversity of product forms, (*b*) the need for further synergistic efforts between processors and dietary guidance, (*c*) consumer considerations (e.g., economic affordability, convenience), and (*d*) lack of nutrition education on the role of processed F&V products in healthy dietary patterns.

Fruit and vegetable product forms. Fresh F&Vs have a limited shelf-life and therefore are often processed to ensure safety and quality. **Figure 5*a*** shows the availability (per capita) of F&V products between 2005 and 2015, and **Figure 5*b*** shows the estimated percentage of available product

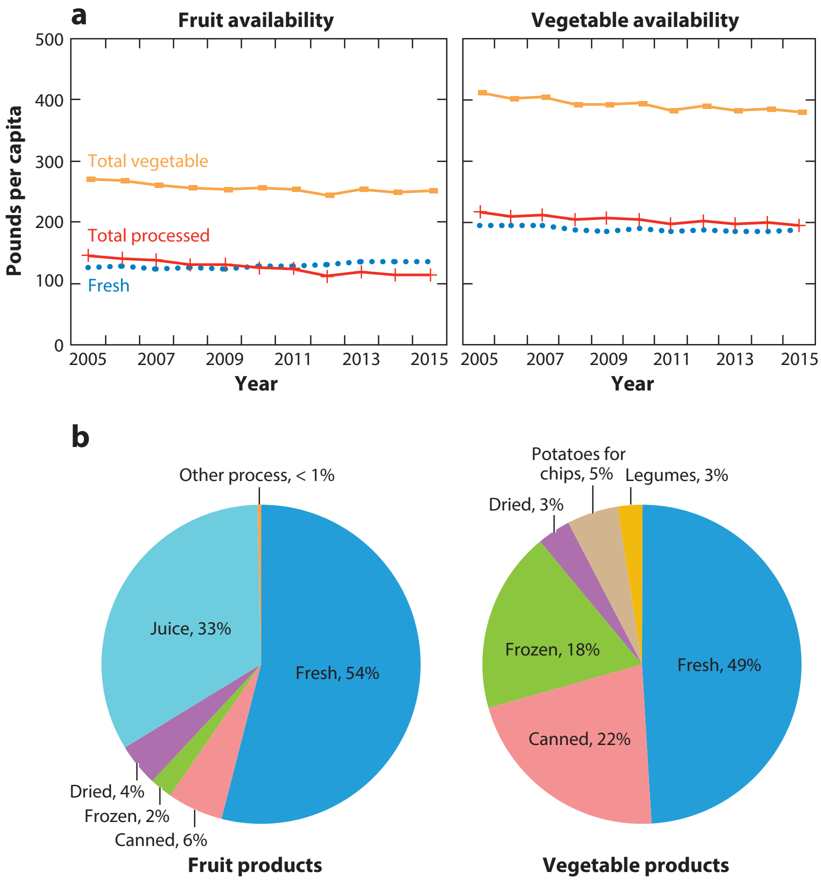

Figure 5

(*a*) Estimated fruit and vegetable availability in the United States from 2005–2015 and (*b*) estimated percentage of product forms in 2015 for fruits and vegetables. Data obtained from USDA ERS (2018).

types in 2015. From the 1970s up to 2011, the total pounds per capita of processed F&V products in the United States exceeded that of fresh products (USDA 2018). Fresh fruit products exceeded processed forms (total pounds per capita) in 2011, whereas processed vegetable products were consistently higher than that of fresh products between 1970 and 2015 (USDA 2018). The most (estimated) available products in 2015 for fruit were fresh and juice while the major forms for vegetables were fresh, canned, and frozen (**Figure 5**). Differences in consumption of WGs versus F&Vs may be due to a variety of inherent differences in the raw material (e.g., shelf-life, sensory-related aspects); however, the diversity of processed products may also be a significant factor. A variety of processed WG products (**Figure 3**) exist and are well integrated into the American diet. Conversely, processed F&V products are comparatively fewer, with fresh or minimally processed produce rather than conventional entrees (e.g., pasta) or staple foods (e.g., bread, rice) available to consumers.

Impact on nutritional and functional quality. From a nutritional standpoint, two main concerns with processed F&Vs products remain: (*a*) loss of nutrients such as vitamins and minerals and (*b*) addition of nutrients that should be limited (i.e., sugar, fat, sodium). Aside from nutrient/

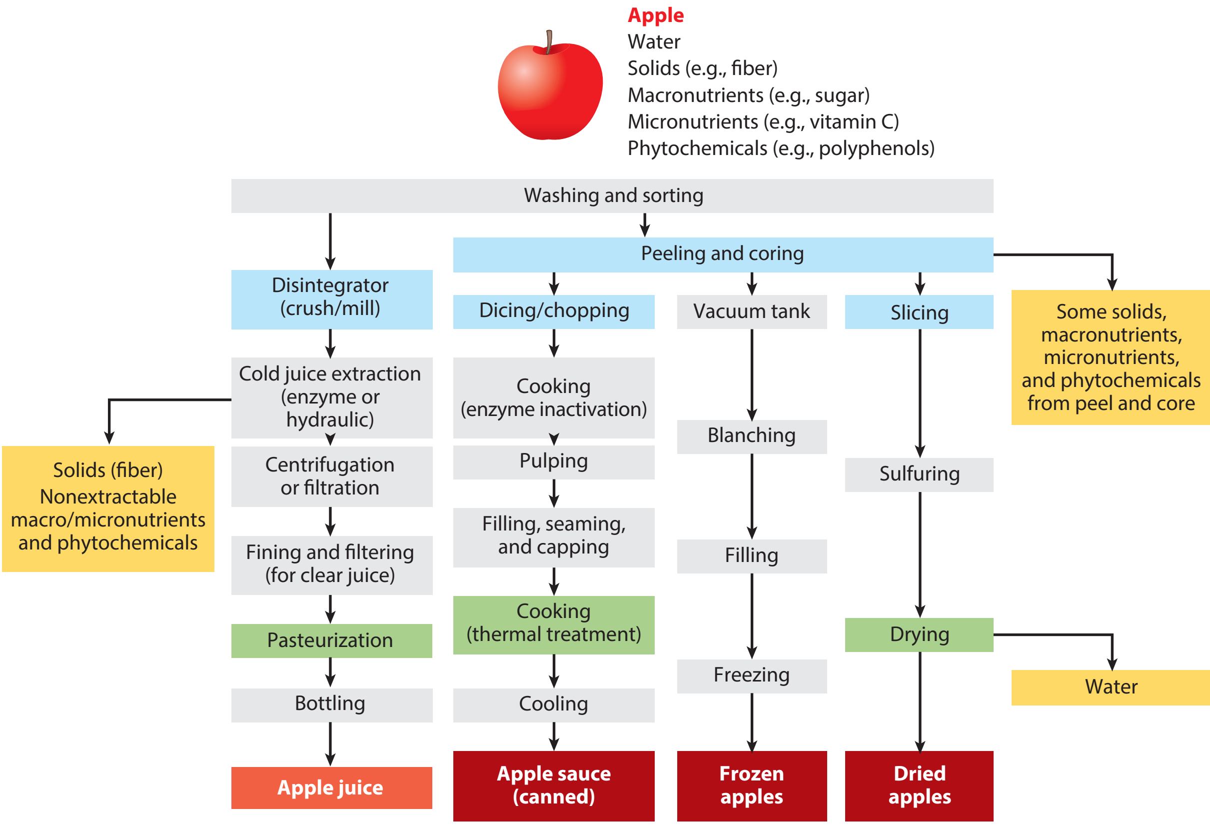

Figure 6

Simplified schematic of processing apple into key consumer products, including dried, frozen, canned, and juiced products. Components that are physically separated during processing are shown (*gold boxes*). Aside from losses during storage (*red boxes*), micronutrients and phytochemicals may be susceptible to oxidation (*light blue boxes*) or thermal degradation (*green boxes*). Figure adapted from Root & Barrett (2004) and Bates et al. (2001).

phytochemical content in the food, their bioaccessibility/bioavailability should also be considered. This includes bioactive compounds, such as polyphenols and carotenoids, that could remain trapped within cell wall materials or remain associated with fiber, thereby limiting or preventing absorption (Palafox-Carlos et al. 2011).

Figure 6 schematically depicts the steps of apple processing to highlight where nutrients are potentially gained and lost. A broad comparison of nutrients from apple products is shown in **Table 5**, illustrating the impact of product transformation on nutritional quality. Apples were selected as a representative example due to their popularity in the diet and their existence as various product forms. However, specific nutrient losses vary across F&V (Rickman et al. 2007a) type and product form. The following sections provide a general overview of frozen, canned, juiced, and dried F&V product forms and the effects of their respective processing on nutritional and functional quality of F&V products.

Fresh F&Vs are often assumed to have higher nutritional value compared to processed forms because of the limited exposure to processing and lack of added ingredients (e.g., sugars, fats, sodium). However, it should be noted that fresh produce is also susceptible to nutrient losses. In particular, vitamin C is known to undergo rapid degradation during the postharvest period

Table 5 Nutrient profiles of apple as different product forms.

Nutrients	Value per 100 g				
	Apple, raw with skin[b]	Apples, frozen, unsweetened[c]	Apples, canned[d]	Apple juice, unsweetened[e]	Apples, dried[f]
Macronutrients[a]					
Water (g)	85.56	86.85	82.28	88.24	31.76
Energy (kcal)	52	48	67	46	243
Protein (g)	0.26	0.28	0.18	0.1	0.93
Total lipid (g)	0.17	0.32	0.43	0.13	0.32
Carbohydrate, by difference (g)	13.81	12.31	16.84	11.3	65.89
Fiber, total dietary (g)	2.4	1.3	2	0.2	8.7
Sugars, total (g)	10.39	10.1	14.84[g]	9.62	57.19
Minerals[a]					
Calcium, Ca (mg)	6	4	4	8	14
Iron, Fe (mg)	0.12	0.18	0.24	0.12	1.4
Magnesium, Mg (mg)	5	3	3	5	16
Phosphorus, P (mg)	11	8	6	7	38
Potassium, K (mg)	107	77	70	101	450
Sodium, Na (mg)	1	3	3	4	87
Zinc, Zn (mg)	0.04	0.05	0.05	0.02	0.2
Vitamins[a]					
Vitamin C, total ascorbic acid (mg)	4.6	0.1	0.2	0.9	3.9
Thiamin (mg)	0.017	0.013	0.009	0.021	0
Riboflavin (mg)	0.026	0.011	0.01	0.017	0.159
Niacin (mg)	0.091	0.042	0.081	0.073	0.927
Vitamin B_6 (mg)	0.041	0.034	0.044	0.018	0.125
Folate, DFE (µg)	3	1	0	0	0
Vitamin B_{12} (µg)	0	0	0	0	0
Vitamin E (alpha-tocopherol) (mg)	0.18	NA	0.21	0.01	0.53
Vitamin K (phylloquinone) (µg)	2.2	NA	0.6	0	3
Phytochemicals[h]					
Cyanidin (mg)	0–4.9	NA	NA	NA	NA
Epicatechin (mg)	1.8–19.16	5.1–9.3	1.2–9.3	9.03	27.7
Catechin (mg)	0–3.4	1.5–6.5	0.9–3.1	4.61	5.6
Procyanidins (mg)	14.56	29.3–56.2	6.5–81.4	9.02	150.5
Quercetin (mg)	0.52–19.76	NA	2	1.04	NA

[a]Macronutrient, mineral, and vitamin data were obtained from the USDA National Nutrient Database for Standard Reference based on NDB numbers 09003, 09014, 09008, 09016, and 09011 for raw, frozen, canned, juice, and dried apples, respectively (**https://ndb.nal.usda.gov/ndb/**).
[b]1 cup = 125 g (quartered or chopped).
[c]1 cup = 173 g (sliced).
[d]1 cup = 204 g (sliced).
[e]1 cup = 248 g.
[f]1 cup = 86 g.
[g]The high sugar content is due in part to the addition of sugar in this product.
[h]Phytochemical values were derived from the USDA Database for the Flavonoid Content of Selected Foods (**https://www.ars.usda.gov/ARSUserFiles/80400525/Data/Flav/Flav_R03-1.pdf**) NDB numbers 09504, 09503, 09501, 09502, 09003, and 09500 for raw apples and 09019 for quercetin value of canned apples. Values for juice were obtained from Phenol Explorer (**http://phenol-explorer.eu**) [nonalcoholic beverages, e.g., apple (cider), pure juice]. All other values were derived from previous reports by Blanda et al. (2008), Le Bourvellec et al. (2011), and Corey et al. (2011).
Abbreviations: DFE, dietary folate equivalent; NA, not available; NDB, nutrient database.

(Bouzari et al. 2015). Some nutrients (e.g., vitamin C) can be substantially degraded as a result of additional processing (**Table 5**); however, other nutrients are more stable and some similarities in nutrient profile can exist across thermally processed forms (e.g., frozen and canned) and fresh products (Rickman et al. 2007a,b). Overall, vitamins (water and fat soluble) and bioactive phytochemicals (polyphenols and carotenoids) tend to be more susceptible to process-induced losses from oxidation or thermal degradation. Conversely, minerals are generally stable against degradation but can be inadvertently leached from F&Vs during washing or blanching (Kmiecik et al. 2007, Rickman et al. 2007a).

Frozen fruit and vegetable products. Frozen products have continued to gain popularity since the introduction of the household refrigerator in the 1940s and contribute significantly to dietary F&V consumption (Storey & Anderson 2018). Freezing is able to preserve many sensory properties (flavor and color) and nutrients while limiting or preventing microbial growth (De Ancos et al. 2012). However, the formation of ice during the freezing process often results in undesirable alterations in texture via tissue damage, stresses on cell volume, and dislocation of water (Chassagne-Berces et al. 2010).

In terms of nutritional quality, freezing can be favorable for retaining vitamins, minerals, and certain bioactive phytochemicals by lowering the temperature and water activity through solidification, thereby limiting available water for chemical/biochemical reactions and microbial growth (De Ancos et al. 2012). However, frozen products can exhibit losses of vitamins and bioactive compounds during storage as some biochemical, physical, and chemical reactions still occur (De Ancos et al. 2012). Riboflavin, ascorbic acid, and α-tocopherol have been reported to be stable in frozen F&Vs (Bouzari et al. 2015), whereas carotenoids such as β-carotene are likely to degrade (Bouzari et al. 2015, De Ancos et al. 2012). Polyphenols (e.g., flavonols and anthocyanins) have been reported to be stable at $-20°C$ for at least 12 months in certain varieties of cherries, berries, and red grapes (Samec & Piljac-Zegarac 2015).

Canned and thermally processed fruit and vegetable products. Although some consumers perceive more highly processed foods, such as canned foods, to be less nutritious, options without added salt and added sugar provide important nutrients in similar quantities as their fresh or frozen counterparts (Miller & Knudson 2014). Thermal processing, traditionally done in a retort, produces a commercially sterile and stable product. Although this process inactivates enzymes and microorganisms, inevitably various thermolabile compounds degrade as well. Advances in flexible retort pouches and aseptic processing/packaging, which allow for lower overall processing loads, have allowed for improved food quality compared to traditional canning (Awuah et al. 2007).

Canned and thermally processed foods undergo substantial vitamin C losses, as vitamin C is highly sensitive to oxidation and thermal degradation. Compared to freezing, which can induce losses averaging at 50% but ranging from 10% to 80%, the average loss of vitamin C in canned products is estimated to be greater than 60% (Rickman et al. 2007a). Although more stable, other water-soluble compounds, such as minerals, are susceptible to leaching, which would likely decrease final nutrient value of the food unless the drained liquid in the can is also considered. Yet, it is important to note that thermal processing does not always have a negative impact on all constituents. Bioactive phytochemicals in plants exist within cellular plant structures (e.g., cell walls, organelles). In some F&Vs, these entrapped compounds may not be readily released from the raw fruit/vegetable food matrix during normal digestion. Thermal processing can aid in breaking down structural plant components that would otherwise act as barriers and prevent the release of certain compounds. An example of this is the bioavailability of lycopene from tomato paste compared to fresh tomatoes. Canned tomato paste undergoes intense processing conditions that structurally disrupt the native tomato matrix. Although other compounds can still degrade during this process, the bioavailability of lycopene increases (Gartner et al. 1997), as it is liberated from the food matrix (van het Hof et al. 2000). Aside from releasing phytochemicals, thermal processing can also affect bioaccessibility by breaking down insoluble phytochemical–polysaccharide complexes or by forming resistant starch, which could limit absorption of lipids (Furrer et al. 2018, Mercier 1979).

Juiced fruit and vegetable products. A major portion of available fruit products in the United States is made up of 100% juice (USDA 2018). Although lower in fiber, commercial 100% fruit juice provides many valuable nutrients and phytochemicals present in fresh fruit (**Table 5**). Although typical home juicing may not fully extract the phytonutrients present in the fruit, commercial juice processing often incorporates enzymes (e.g., pectinase/cellulose), heat treatments, or other processing aids in extraction to increase yield (Clemens et al. 2015). Theoretically, mainly fruit solids (e.g., fiber) are removed during the juicing process; however, some amount of unextractable compounds (e.g., micronutrients, polyphenols) often remains in the solid residue. Although losses in nutrient profile may occur as a result of processing and heat treatment, juice may be a more bioavailable source of phytochemicals such as polyphenols because of the lower fiber content compared to fresh fruit (Kris-Etherton et al. 2002, Quiros-Sauceda et al. 2017).

Dried fruit and vegetable products. Dried fruit consumption was found to be associated with improved diet quality and reduced obesity in Americans (Keast et al. 2011). Drying is a fundamental processing technique that preserves foods by lowering the water activity. Traditional drying techniques (e.g., hot air drying) can degrade product quality because of the long exposure time of the product to high temperatures. Optimization of drying techniques for specific F&V products or use of alternative strategies that offer shorter processing times (e.g., microwave drying) can potentially help to improve the nutritional and functional quality of the product (Santos & Silva 2008). Zhang et al. (2015) have reviewed developments in drying technologies, including infrared, dielectric, freeze-drying, and combination technologies, and Omolola et al. (2017) have reviewed the effects of drying on nutrient/phytochemical content. Similar to juice, dried F&Vs represent a nutrient-dense product. However, unlike juice, dietary fiber is not substantially altered (**Table 5**) because moisture, rather than solid matter, is removed to produce the final product (**Figure 6**). Sugar content (per product weight) of dried fruits is high compared to fresh forms because of the substantial water loss.

Potential Directions for New Fruit and Vegetable Products

Advances in processing strategies can allow for product quality enhancement by increasing stability or bioavailability of bioactive compounds, concentrating valuable nutrients, or even selectively separating out undesired compounds. One example of this is that 100% juice (i.e., the low-fiber, concentrated phytochemical, and sugar–liquid portion of a fruit or vegetable) may be processed to selectively remove sugar. Ultrafiltration has been used by the dairy industry to remove lactose from milk (**https://fairlife.com/our-nutrition/**). Ultrafiltration might also be applied to juice as it has been optimized to reduce membrane fouling and to separate polyphenols from sugars in pineapple juice (Wei et al. 2007). Innovations in thermal and nonthermal processing have also allowed for better retention of thermolabile phytochemicals and other compounds. High-pressure processing and high-intensity pulsed electric field technologies have been shown to preserve total carotenoid content and enhance bioaccessibility in fruit juices compared to thermal processing (Rodriguez-Roque et al. 2016).

Although many process innovations can be applied to the generation of new F&V products, these efforts impact consumption only if the benefits of new products can be clearly communicated to consumers and the quality is high. The current DGA clearly distinguish whole fruits (including fresh, canned, frozen, and dried forms) from 100% fruit juices. Although this provides simple guidance for the general American consumer, it also limits the ability to innovate in new product forms that may not clearly fall into these categories. For example, a low-/no-sugar ultrafiltered juice product would not have a clear category in current guidance despite the fact that it may be theoretically more nutrient dense than 100% juice and whole fruit but still low in sugar and fiber. Although WG consumption gaps have been improved through a combination of communication strategies, product definition, and guidance, F&Vs lack such a complete approach. New strategic standards (or sets of definitions) are needed to better facilitate F&V product innovation and foster increased consumption.

OTHER CHALLENGES THAT LIMIT FRUIT AND VEGETABLE CONSUMPTION RELATIVE TO WHOLE GRAINS

Despite innovations and potential benefits of F&V processing, a tight connection between research and application is still lacking for F&Vs relative to WGs. A variety of challenges persist for consumers when aiming for adequate F&V consumption. Among the most prominent are economic affordability of products, convenience, and a lack of nutrition education. Generally speaking, WG cereals have relatively high nutrient-to-price ratios (Darmon & Drewnowski 2015). By contrast, F&V purchases are associated with higher diet costs (Keim et al. 2014). However, the cost of F&Vs varies widely depending on the product type and product form. Most Americans do not achieve the recommended servings of F&Vs, but one study reports that of the Americans that do meet the recommended F&V intake, fresh product forms remain the primary product form consumed (Moore et al. 2016). Unfortunately, fresh F&Vs are often associated with higher cost.

Select vegetables have been reported to have similar nutrient content per calorie across canned, frozen, and fresh forms (Miller & Knudson 2014). Despite the similarity in nutrient content, the price per edible cup is often the highest for fresh vegetables, followed by frozen, and then canned as the cheapest of the three options. Drewnowski (2013) assessed the affordability of vegetable products compared to the Nutrient Rich Foods (NRF) index and found that the although tomato juices/soups, dark vegetables, yellow vegetables, and sweet potatoes had the highest NRF scores per dollar in the study, they were consumed less frequently compared to products (e.g., raw tomatoes and potato chips) that are less affordable and have lower NRF scores. This suggests that careful selection or recommendation of select processed F&V products can be leveraged to enhance nutrient intake while limiting the increase to diet cost. In a systematic review, Darmon & Drewnowski (2015) specify that although healthier diets are generally more expensive, it is possible to achieve a high-quality diet on a low budget. However, these lower budget diets were not necessarily perceived as palatable, which makes it challenging to effectively encourage the dietary recommendations. Processed forms of F&Vs, including new innovative products, can be a cost-effective alternative to fresh products for low-income families (Miller & Knudson 2014). Aside from the economic aspect, another limiting factor for increasing F&V consumption is the perceived (or real) pressure of time constraints (Ragaert et al. 2004), which could be remedied with new convenient products (Candel 2001).

Finally, lack of a clear definition makes it challenging for consumers to unambiguously determine serving sizes of various F&V products. The current DGA provide guidance on F&V cup and ounce equivalents (USDA & DHHS 2015). As examples, 100% orange juice and strawberries are listed as equivalent with a half cup of raisins while one cup of raw spinach is equivalent to a half cup of green beans. Aside from these examples, the definition of one serving for F&Vs remains vague. As new processed fruit/vegetable products are developed, adjustments in guidance and policy are needed to clearly articulate to the public how these products translate to the recommended serving amounts. It is important to build on the guidance provided for WGs, which has facilitated both product innovation and consumer adoption of improved products in the F&V space. With processed foods still holding a controversial place with many consumers, it remains critical to remember that the broad category of processed foods, including WG and F&V products, is wide and heterogeneous (Poti et al. 2015). Development and ultimate selection of products that align with DGA principles can be important mechanisms to meet dietary guidance and deliver health benefits of WGs and F&Vs.

DISCLOSURE STATEMENT

M.G.F. has served as a consultant for Welch's and General Mills Inc. and has received research funding from both organizations. M.G.F. also serves as a member of the board of Sensient Technologies Corporation. All other authors have no conflicts to declare.

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