SNACK FOODS

Processing, Innovation, and Nutritional Aspects

Edited by

Sergio O. Serna-Saldivar

CRC Press
Taylor & Francis Group

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

First edition published 2022
by CRC Press
6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487-2742

and by CRC Press
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN
CRC Press is an imprint of Taylor & Francis Group, LLC

This book provides a technical review of snack foods. Emphasis is made in flavored salty snacks commonly used as finger foods including popcorn, wheat-based snacks (crispbreads, pretzels, crackers), lime-cooked maize products (tortilla chips), potato chips, peanuts, almonds, and snacks from fruits/vegetables, milk, animal and marine sources.

Library of Congress Cataloging-in-Publication Data

Names: Serna Saldívar, Sergio R. Othón, editor.
Title: Snack foods: processing, innovation, and nutritional aspects / edited by Sergio O. Serna Saldivar.
Description: First edition. | Boca Raton: CRC Press, [2022] | Includes bibliographical references and index.
Identifiers: LCCN 2021040007 (print) | LCCN 2021040008 (ebook) | ISBN 9780367646875 (hardback) | ISBN 9780367653514 (paperback) | ISBN 9781003129066 (ebook)
Subjects: LCSH: Snack foods. | Food science.
Classification: LCC TX740.S6227 2022 (print) | LCC TX740 (ebook) | DDC 664/.6--dc23
LC record available at https://lccn.loc.gov/2021040007
LC ebook record available at https://lccn.loc.gov/2021040008

ISBN: 978-0-367-64687-5 (hbk)
ISBN: 978-0-367-65351-4 (pbk)
ISBN: 978-1-003-12906-6 (ebk)

DOI: 10.1201/9781003129066

Typeset in Times
by Deanta Global Publishing Services, Chennai, India

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Preface

It has been almost two decades since Technomic Publishing Company produced the first edition of the *Snack Foods Processing* by my former professors Drs. Edmund Lusas and Lloyd W. Rooney. Unfortunately, both professors recently passed away and the much-needed and updated second edition became an orphan. It is for me a privilege to continue their legacy through the production and edition of this comprehensive book.

This book was conceptualized to thoroughly cover practical and scientific aspects related to the chemistry, technology, processing, functionality, quality control, analysis, and nutrition and health implications of the wide array of snacks derived from the major four groups of foods that sustain humankind (grains, fruits/vegetables, milk, and meat/poultry/seafood).

During the past 20 years, it has been massive improvements and advancements in the snack food industries that generate close to 520 billion dollars of annual sales. This new edition is based on the spirit of the original but with several new topics influencing food product development today: innovation, new emerging technologies, and nutritious and health-promoting snacks. The new volume is the result of a need to cover the intriguing world of snack food manufacturing in a deep format. The snack food industry has developed from a craft to technological industries around the globe. The mechanization of the food industry and the development of raw materials suited for these products have made it possible to produce a wide array of high-quality snacks with a high processing efficiency. Snack foods are commonly manufactured from low-cost raw materials such as cereal dry-milled fractions, starches, and oils, and the finished products are usually sold at a very high profit. The changes in trends in food consumption have always favored the snack food sector. For many years in developed countries, annual snack sales had grown more than the population increase, mainly due to convenience, long shelf life, and recently even through the COVID-19 pandemic. Nowadays, the consumer demands novel snacks with better nutritional attributes and processors have to innovate to keep or expand their markets. In addition, nutraceutical or functional additives are starting to form part of snack food developments. The industry has to adapt to these new developments and develop large-scale processes that increase manufacturing efficiency and reduce labor costs and risk of contamination, with pathogenic bacteria, mycotoxins, and toxicological compounds generated during deep-fat frying operations.

This book provides a technical review emphasizing flavored salty snacks commonly used as finger foods, including popcorn, wheat-based snacks (crispbreads, pretzels, crackers), lime-cooked maize products (tortilla chips and corn chips), extruded items (expanded and half products or pellets), potato chips, peanuts, almonds, tree nuts, and snacks from fruits/vegetables, milk, animal, and marine sources. The introductory chapter deals with the different categories of snacks and the statistics of volume, sales, and *per capita* consumption of these items. The following four chapters comprise the main or major unit operations used to process snacks: thermal processes, frying, seasoning, and packaging, including the novel and emerging technology of 3D printing. These sections accentuate emerging technologies and engineering and design aspects. Then, the book covers the most relevant raw materials used in snack operations: cereal-based refined grits, starches, and flours, followed by chapters for oils, seasoning formulations, and packaging materials. The core of the book is comprised of ten chapters, which describe the production and manufacturing of grain-based snacks including popcorn; wheat-based; alkaline or lime-cooked (corn and tortilla chips); extruded products; other grains such as legumes, pulses, oilseeds, and pseudocereals; and snacks derived from potatoes, almonds, tree nuts, fruits/vegetables, milk, and animal/poultry/seafood sources. Each of these manufacturing chapters includes flowcharts of the processes, relevant information in tables, and recent innovations and trends. The book is completed with chapters related to quality assurance and control procedures used by the various segments of the snack food industries and two chapters related to the nutritional and nutraceutical and health-promoting properties of all classes of snacks. At the end of each chapter, a set of updated references are included to provide key scientific material useful to get deeper into specific topics and expand knowledge.

This book was conceptualized and written to guide scientists, technologists, food engineers, technical salespeople, students, nutritionists, and even health practitioners interested in how the different classes of snacks are made and their relevant role in human nutrition and well-being.

The editor acknowledges the time, effort, and kind contributions of all authors and the Editorial Project Manager Stephen Zollo and Editorial Assistant Laura Piedrahita who dedicated many hours to this endeavor during the past two years. I especially recognize their tireless efforts through the completion of this volume.

Lastly, I certainly hope that this book will positively affect scientists, students, and food developers to upgrade snack food quality and health for the nearly eight billion people who presently inhabit the globe.

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- Processing and biotechnology of cereal grains and legumes
- Nutraceutical properties of foods
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1 Overview and State-of-the-Art of the Snack Food Industry

Sergio O. Serna-Saldivar

CONTENTS

1.1 INTRODUCTION

Snacks are defined as foods served or taken informally in small amounts between meals and are further described as light, casual, or hurried meals. Most snacks are ready-to-eat (RTE) items high in oil and generally flavored with salt or salt-based flavorings although many sweet fruit/vegetable-based snacks are growing in relevance throughout the globe. It is hard to establish the borderline between snacks, collations, and confectionary products, so in this book we will primarily stress the production and features of shelf-stable savory snacks containing low moisture. The major

DOI: 10.1201/9781003129066-1

distinction of snacks is that they are shelf-stable products at room temperature because most are subjected to dehydration by frying, toasting, baking, or salting. The packaging of these products is aimed to preserve freshness and avoid moisture uptake and oil rancidity. From the microbial viewpoint, most snacks do not pose health risks because pathogenic bacteria and molds require higher water activities (A_w) to prevail and grow. Most snack processors focus their technologies to enhance the shelf-life of their products from the rancidity or fat oxidation and texture standpoints. These critical parameters are mainly controlled by the selection of the proper frying oils, the frying process, the use of artificial or natural additives, and especially the packaging technology, which in most instances employ materials that exclude moisture, oxygen, and UV light to protect product crispiness and rancidity.

Today, consumers are seeking snacks that are aligned with their individual diet preferences, whether it's vegan, vegetarian, keto, or gluten free. The clean-label movement has created an array of products manufactured with clean ingredients and additives, and therefore more snack mixes or blends based on dry or intermediate moisture fruits, grains, legumes, and tree nuts are being developed. The other positive trend of the industry is the snacking of high protein and low-carb products mainly produced from dry and intermediate moisture meats and marine species.

Overall, the current trend of the snack industry is the development of nutritious snacks with lower amounts of fat and sodium, higher amounts of proteins and dietary fiber, with GRAS additives (green or clean label), and a better profile of fatty acids especially in terms of the ratio of unsaturated:saturated fatty acids.

The objective of this chapter is to introduce the reader to the scope of the snack industry including the historical preview of major snacks, statistics of volume and sales, and the importance, advancements, innovations, future trends, and constraints of the industry.

1.2 CLASSIFICATION OF SNACK FOODS

Snacks have always been an important part of life, and these foods represent a relevant segment of the food industry globally especially in developed countries. The snack food market is continually evolving and adapting to the new consumers' trends. During this century, the industry has gradually adapted to fulfill the demands of millennials and recently to forced patterns due to the COVID-19 pandemic. Snacking is increasing from factors such as increases in one-person households, a higher proportion of working parents and more school-age children obtaining their own meals, a highly mobile population, and the availability of RTE snacks in convenience stores and vending machines (Riaz 2004). From the processing viewpoint, the industry is continuously innovating and evolving to generate new foods packaged in attractive and functional materials to preserve their freshness for longer periods of time.

1.2.1 Current Commercial Products

Snacks are broadly classified according to their food source and to their manufacturing process (Tables 1.1 and 1.2). Practically all food groups have important examples of snacks. Undoubtedly, the most relevant and sold worldwide are those derived from grains, mainly cereals, followed by tubers. These products are fabricated taking advantage of the functionality of the gelatinized starch. Many other types of snacks are sourced from tree nuts, fruit/vegetables, milk, different meats, and marine products. Independently of the food source, practically all snacks are shelf stable at room temperature because of their low moisture content and water activity (A_w). The only exception is snacks derived from milk such as yogurt, cheeses, mousse, and flans, which commonly require refrigeration. Table 1.1 summarizes the major snack types according to the food source, characteristics, and general nutritional attributes. From the processing standpoint, most commercial snacks fit into the categories of first, second, or third generations (Table 1.2). First-generation snacks are the easiest to manufacture and consist of natural products such as roasted whole grains, peanuts,

TABLE 1.1
Classification of Snack Foods According to Their Food Source and Main Characteristics

Snack Food Source	Main Types of Snacks	Main Characteristics	Major Nutritional Attributes and Constraints
Grain Base			
Cereals	*Corn*: popcorn, parched corn, corn chips, tortilla chips, extruded puffs. *Wheat, oats, and/or rye*: toasted bread or crisps, crackers, pita bread chips, hard pretzels.	Shelf-stable products that contain low moisture and high-fat content commonly produced by conventional, lime, or extrusion cooking processes followed by baking, frying, and seasoning with salt-based flavorings.	Since most products are produced from refined milled fractions and flavored with fat they are considered high caloric and fat products. These snacks are rich in starch and oil and contain relatively low protein, dietary fiber, and micronutrients. The protein is medium to low quality because it lacks lysine and other essential amino acids. Wheat, rye, barley, and even oat products need to be declared on the food label as potential allergens for celiac or gluten intolerant people.
Legumes/oilseeds	Roasted peanuts, Japanese peanuts, soybeans, sesame, pumpkin, and poppy seeds.	Shelf-stable whole products that contain low moisture that in most instances are roasted or toasted and occasionally fried.	Considered nutritious snacks because of their high protein and dietary fiber contents and lipids rich in polyunsaturated fatty acids. Additionally, these grains are rich in phytochemicals that favor human health. Among these products, peanuts and soybeans should be declared as potential allergens in food labels.
Pseudocereals	Puffed and dried amaranth, chia, quinoa, and buckwheat.	Shelf-stable whole products that contain low moisture that in most instances are toasted or puffed for use in the preparation of granola bars.	Considered nutritious snacks because of their high protein and dietary fiber contents. Additionally, these grains are rich in relevant phytochemicals (antioxidants) that prevent oxidative stress and chronic diseases.
Tubers, Fruits, and Vegetable-Based			
Tubers	Regular and fabricated potato chips.	Shelf-stable savory snacks that contain low moisture and high lipid content that are commonly produced by deep-fat frying and salting or seasoning with salt-based flavorings.	Since most products are produced from sliced potato or potato flour and deep fat fried they are considered highly caloric due to their high-fat content. These snacks are rich in starch and oil and contain very low levels of protein, dietary fiber, and micronutrients. Besides, these snacks can develop significant levels of acrylamide, which is considered an important toxic compound.
Tree nuts	Toasted or roasted almonds, macadamia, pecans, pistachios, cashews, walnuts, and pine nuts.	Shelf-stable whole products that sustain minimum process because they are commonly only roasted. These products are usually sold in mixes with fruits or other nuts or employed for the production of snack bars.	Among snacks, tree nuts are considered one of the most nutritious because of their natural high fat, protein, and dietary fiber contents. Besides, their lipids are rich in polyunsaturated fatty acids, phospholipids, phytosterols and vitamin E, or tocopherols and other phytochemicals that favor human health mainly through the prevention of cardiovascular diseases. The main concern with almonds and tree nuts is their potential allergenicity.

(*Continued*)

TABLE 1.1 (CONTINUED)
Classification of Snack Foods According to Their Food Source and Main Characteristics

Snack Food Source	Main Types of Snacks	Main Characteristics	Major Nutritional Attributes and Constraints
Fruits	Dehydrated fruits, osmotic dehydrated foods, fruit bars.	Minimum processed snacks are usually obtained after dehydration with conventional means or novel technologies (osmotic, vacuum, or freeze-drying). The products have low Aw because of the moisture removal and concentration of natural sugars associated with the fruit matrix.	Snacks from fruits are rich in soluble sugars, dietary fiber, and an array of phytochemicals that favor human health. In addition, they are practically free of lipids and therefore are not as caloric dense as other snacks that are commonly fried.
Vegetables	Dehydrated vegetables, fried vegetables,	Minimum processed snacks are usually obtained after dehydration with conventional or novel technologies and alternatively by deep fat frying. The products have low Aw because of the moisture removal during drying or frying.	Snacks from vegetables are rich in dietary fiber, phytochemicals that favor human health, and are low in calories.
Milk-Based			
Dairy	Yogurts, cheeses, puddings, mousses, flans.	Snacks from dairy products generally require refrigeration and are produced after the coagulation of casein with enzymes or acidity created by fermenting lactic acid bacteria.	Dairy-based snacks are rich in good quality protein, soluble sugars, milk fat, and highly bioavailable calcium. However, the major constraints of these products are the potential hazards in terms of pathogenic bacteria and lactose intolerance.
Animal and Marine-Based			
Meats	Pork rinds, jerkies, dry meats, dry-cured hams, sausages.	Shelf-stable snacks from animal products are generally produced after solar or artificial dehydration, salting, or dry curing. The popular pork rinds are obtained after deep-fat frying of pork skin.	Meat-based snacks are rich in good quality protein and practically devoid of sugars and carbohydrates so they are demanded by people following the keto diets. In addition, they provide highly bioavailable iron and zinc. The major constraint of these products is their high susceptibility to pathogenic bacteria and their high contents of saturated fat and cholesterol.
Marine	Dehydrated fish, dry crustaceans.	Shelf-stable snacks from fish and crustaceans are generally produced after solar or artificial dehydration, salting, and pickling.	Marine-based snacks are rich in good quality protein and practically devoid of sugars and carbohydrates so they are demanded by people following the keto diets. In addition, they provide highly bioavailable iron and zinc. The major constrain of these products is their susceptibility to pathogenic bacteria contamination and for crustacean products like dehydrated prawns and shrimp their high cholesterol content.

TABLE 1.2
Classification of Snack Foods According to Conventional and Emerging Manufacturing Procedures

Category	Process	Products
Conventional Technologies		
First generation	Minimum processed snacks obtained from grains and fruits from natural products.	Popcorn, peanuts, other dehydrated whole grains, almonds, tree nuts, and dehydrated fruits and vegetables. Regular fried potato chips also belong to this category.
Second generation	Most popular category of snack foods. Snacks are obtained after simple shaping of doughs or dry milled fractions forced through a extruder (direct expanded products). Raw materials include various types of flours and grits.	Includes extruded corn chips, tortilla chips, and a wide array of direct extruded items such as corn puffs and curls. Toasted crisps, pita chips, hard pretzels, and fabricated potato chips or sticks are also included in this category.
Third generation	Most elaborated products also called half products or pellets generally produced by a two-step extrusion process (cooking and forming extruders). The formulation of these snacks uses a wide array of ingredients. These products required additional processes to reach the consumer such as baking and deep-fat frying. Most pellets are commonly processed via frying.	Imitation pork rinds, wheel-shaped puffs, or sticks obtained after thermal treatment or deep-fat frying of half products or pellets.
Novel Emerging Technologies		
Coextruded snacks	In this relatively new process two different types of raw materials are extruded from one die. These raw materials can come from two extruders or one extruder equipped with one pump. Coextruded snacks have two recognizable parts: an external cover or crust and an internal filling.	Cereal-based tubes filled with cheese or other fillings such as fruit pastes. Many commercial extruded cookies or crackers with salt-based or sweet fillings are produced with this technology.
Supercritical fluid extrusion	In this process, supercritical CO_2 is injected into the extruder barrel to create viscosity changes which affect the properties of second generation or puffed snacks especially in terms of crumb texture, radial expansion, color and flavor.	Extrusion with liquid CO_2 presents the main advantage of minimizing the loss of heat-labile nutrients that are usually lost during conventional thermoplastic extrusion processes.
3-D printed snacks	The 3-D printing process involves building 3-D forms from a drawing sample designed by a computer program. The potential snacks can be printed with special extruders or food-grade syringes that deposit the product through a nozzle. The printing is controlled by computers. Among the various 3-D printing technologies the most promising and practical is the extrusion-based printing that forces raw materials in the form of pastes through the specially shaped nozzle of the printer. Potential novel snacks that can be manufactured with this technology are dough-based bakery items, meat and fruit pastes, and cheeses.	The 3-D printing technology allows producers to tailor-make personalized snacks in terms of nutrition, shape, and organoleptic properties. The major constraints of this technology are production cost and large-scale production.

nuts, dried fruits and vegetables, popcorn, and regular potato chips. Most snacks consumed today belong to the category of second generation. These include simple formed products mainly obtained after direct extrusion (i.e., corn chips, expanded puffs, balls, and curls) or by sheeting/forming and baking/frying such as fabricated potato chips, tortilla chips, granola bars, pita chips, crisps/toasted breads, and hard pretzels. The most elaborated category in terms of ingredients and processing is the third-generation snacks commonly manufactured after two sequential extrusion steps known as cooking and forming that yield first pregelatinized dense pellets or half products which are further processed with deep-fat frying, baking, or microwave cooking to reach the consumer.

1.2.2 Emerging Products and Technologies

Novel processes that have been recently employed to produce innovative snacks are coextrusion, CO_2 extrusion, and 3D printing. Coextruded snacks are produced in a distinct type of extruder equipped with a special die that allows the coextrusion of two contrasting types of materials: an outer covering generally produced from starchy feedstocks and an inner filling consisting of salt-based flavorings or sweets.

Supercritical fluid extrusion, also known as SCFX, was patented by Rizvi and Mulvaney (1992) in the early 1990s. In this process, supercritical CO_2 is injected into the extruder barrel to create viscosity changes, which affect the properties of extrudates especially in terms of crumb texture, radial expansion, color, and flavor. Extrusion with liquid CO_2 presents the main advantage of coextruding with a nontoxic and relatively inexpensive supercritical carbon dioxide. SCFX has been applied for the manufacturing of novel puffed snacks at lower temperatures with improved texture, color, and taste minimizing the loss of heat-labile nutrients that are usually lost during conventional thermoplastic extrusion (Rizvi et al. 1995, Sharif et al. 2014, Panak-Balentić et al. 2017).

The novel and disruptive technology of 3D printing has been successfully used for the manufacturing of innovative snacks. Most frequently, different food products are printed with special extruders or food-grade syringes that deposit the product through a nozzle. The most advanced 3D printing technology allows producers to tailor-make personalized snacks in terms of shape, color, texture, and flavor on computers or related electronic devices. Among the 3D printing technologies, the most promising and practical is the extrusion-based printing that forces raw materials in the form of pastes through the specially shaped nozzle of the 3D printer. Potential novel snacks foods that can be developed using this technology are dough-based bakery items, meat pastes, and cheeses.

1.3 HISTORICAL PREVIEW AND GENERAL PROPERTIES OF SNACKS

Snack foods have their origin thousands of years ago likely since the men conceived agriculture, became sedentary, and developed simple processes to prolong the shelf-life of foods. The most antique snacks were grains, dehydrated meats, and marine products. However, the modern snacks available today became popular when they were first packaged for merchandising during the industrial revolution of the 19th century. It was until the first decades of the 20th century when that more snacks became accessible to the general public in Europe and the United States. The boom of the snack industry occurred after the Second World War when the postwar economic surge occurred and many novel snack types were launched into the market as convenient foods.

1.3.1 Popcorn

Popcorn (*Zea mays* L) is one of the oldest snacks and documented as a relevant source of nutrients to ancient American cultures. The special type of maize known as popcorn is regarded as one of the first landraces by many archeologists. It is quite possible that primitive Mesoamericans first discovered the usefulness of popcorn when this flinty wild kernel was unintentionally exposed to heat. To people with no grinding tools other than their own teeth realized that an unpromising food became tender, tasty, and attractive. The indigenous Mesoamericans knew popcorn before the Spaniards conquered America. The great Aztec culture honored one of the gods by scattering parched or popped corn, called *momochitl*, to emulate white flowers (Weatherwax 1954). The other great pre-hispanic Inca culture developed special pottery utensils for popping corn and remains of popped kernels have been often found in Peruvian graves. The oldest positively identified corn poppers date from the Mohican Indian culture of about 300 AD along the northeast coast of Peru. Christopher Columbus documented that when he arrived in San Salvador he observed natives wearing popcorn decorations. A Spaniard document dated 1650 quoted that the Mesoamericans "They toast a certain type of corn until it bursts. They call it pisancalla and use it as a confection." Popcorn also forms part of US history because it was present on the first Thanksgiving day when Quadequina, the brother of the Wapanong chief Massasoit, offered a deerskin bag full of popcorn as a gift to the celebration (Serna-Saldivar 2008a,b).

Historically, it is known that in India and neighboring countries other special types of popped kernels have been traditionally consumed. In this sense, a special type of hard endosperm sorghum (*Sorghum bicolor* L Moench) known as *Shallu*, and several types of millets have been traditionally used by Asian and African cultures (Malleshi and Desikachar 1985, Mishra et al. 2014).

Today, popcorn, especially the one suited for microwave popping (Chapter 9), continues to be one of the most popular snacks all over the globe with an astonishing market of about 10 billion USD in 2020.

1.3.2 Wheat-Based Snacks

There are many indigenous foods derived from ancestral wheat that we still widely consume today. The first sedentary cultures learn to stone-mill wheat and related cereals into flours, which upon hydration and mixing generated doughs that were adequate substrate for yeast and lactic acid bacteria. The unique combination of viscoelastic properties of wheat flour with the fermenting microorganisms resulted in the production of an array of traditional staples still produced by mankind today. The toasting of these primitive flat and leavened breads originated shelf-stable products that evolved into many wheat-based snacks. The major categories of wheat-based snacks thoroughly covered in Chapter 10 are crackers or hard biscuits, granolas, pretzels, pita chips, and toasted or crispbreads.

1.3.2.1 Crackers or Hard or Salt Biscuits

The preparation of biscuits or crackers dates to the early history of mankind and develop into an industry that today ranks among the leaders in the USA snack market. The first prototypes of crackers originated thousands of years ago when men stone-milled their grains and produced flours that were mixed with water and baked directly on fire or ashes to form small unleavened cakes. Remains of these primitive baked products have been found in Swiss dwellings dated more than 8,000 years old. The early Egyptian culture depicted illustrations of the baking operation and cookies served at the royal table in ancient tombs such as the Ramses III dating back to the year 1190 BC (Kulp 1994, Misra and Tiwari 2014).

According to Manley (2000) the word biscuit, which is the synonym for crackers and cookies, is derived from the Latin word *panis biscotus* meaning twice-cooked bread and refers to dried products originally made for mariners of the Middle Ages. The word biscuit is defined in the dictionary of Dr Samuel Johnson published in 1755 as "a kind of hard dry bread, made to be carried to sea," and a secondary one of "a composition of fine flour, almonds and sugar, made by the confectioners." William Shakespeare also refers to ships biscuits in his play *As You Like It* written more than four centuries ago. The early biscuits manufactured for long voyages were produced from just flour, salt, and water. In America, they were known as pilot biscuits or hardtack. Due to their hardness and low moisture content, biscuits were very firm to eat and normally had to be soaked in a beverage or soup to make them appetizing.

The category of crackers or salty biscuits is subdivided into cream, soda, and savory crackers (Chapter 10). Cream cracker biscuits were first introduced in about 1885 by the Irish firm Jacobs. Since then they have maintained a significant place in the sales of biscuits in Britain and have also spread to many other countries around the globe. They should not be confused with soda crackers, which are another traditional type of cracker. The soda cracker or saltines, derived from the cream cracker, is of American origin. The first record of this type of cracker is in 1840. The savory biscuits also known as sandwich crackers are more modern and are generally flavored with cheese-based fillings (Manley 2000).

1.3.2.2 Pretzels

A pretzel is a wheat-based snack food with 800 years of history. According to Terry Groff (2001), it was first produced by a monk in the 12th century as a reward to religious children. The typical pretzel configuration clearly shows a cross in the middle representing the crossed arms of a Christian in prayer. Pretzels are clearly represented on the coat of arms of the bakers of Vienna because these bakers in 1529 heard the digging of a tunnel that the Turks were building to conquer the city. Therefore, the pretzel bakers saved the city. Since then pretzels are the symbol of bakers throughout Europe especially in Germany, Austria, and Switzerland. According to Seetharaman (2014) hard pretzels were introduced to the United States in the 1860s at Lititz, Pennsylvania, and have since become a very popular and healthful snack item.

1.3.2.3 Granolas

Toasted granola pieces were first industrially manufactured in the late 19th century. The invention of the Granola is attributed to Dr James Caleb Jackson in the state of New York in 1863. The original granola was produced from Graham flour (coarsely ground whole wheat flour) and viewed as a healthy food. From the original granola, many other similar products developed mainly consisting of toasted whole grains, wheat-based bakery and toasted pieces, dehydrated fruits and nuts. Granolas were primarily considered as RTE breakfast cereals because they were generally consumed with milk. However, granola bars are viewed as one of the most healthy snacks available in the current market.

There is controversy regarding the invention of the first granola bars. Some credit the innovation to Stanley Mason and others to Herrick Kimball who also claimed the idea for this product in the mid-1970s. The key for the production of flattened bars is the addition of honey or other sweetened syrups, which are blended with many different toasted grains, nuts, and dehydrated fruits. Since then the granola bar market has increased to a multibillion-dollar industry with numerous different types. In the United States, Nature Valley followed by Nature Valley Sweet & Salty Nut and Quaker Chewy accounted for 23.4, 15.6, and 14.4% of the market share in 2017 (https://truenorthgranola.com/blog/what-is-granola-and-granola-history/).

1.3.3 Snack Bars

The category of snack bars is one of the fastest growing within the snack sector because customers, especially millennials and the health conscious perceive food bars as highly nutritional and convenient. The consumption of snack bars is influenced by age, gender, nutritional knowledge of the consumers, and convenience. As a result, the industry has developed numerous options with different nutritional features and numerous flavors and textures. Snack bars are widely available in multiple different flavors and textures depending on the types of cereals grains, other seeds (pulses and pseudocereals), proteins (vegetable and dairy), dehydrated fruits and vegetables, chocolate, and dairy products. The most important common characteristic is that all snack bars are shelf stable at room temperature because of their relatively low water activity (A_w) and in many instances fortified with micronutrients (vitamins and minerals) and nutraceuticals like fiber, antioxidants, and healthy fats such as omega-3 and DHA.

As a result of the great interest in snack bars, the industry is currently producing cereal-based, energy, protein, 40-30-30, gluten-free, fruit-mixed, nut-mixed, flavored with chocolate and other coatings with different nutritional profiles and functional properties (Estevez et al. 1995, Gonzales and Draganchuk 2003, Sun-Waterhouse et al. 2010, Aramouni and Abu-Ghoush 2011, Hogan et al. 2012, da Silva et al. 2014, Ferreira et al. 2015, Da Silva et al. 2016, Constantin and Istrati 2018, Munir et al. 2018, Ramirez-Jimenez et al. 2018). In recent years, the demand for high-protein snack bars has specially grown with some products containing up to 35% protein and bars are more commonly formulated with micronutrients (vitamins and minerals) and nutraceuticals like insoluble and soluble fiber sources, natural antioxidants, and healthy fats such as omega-3 and DHA (Aramouni and Abu-Ghoush 2011, Constantin and Istrati 2018). Table 1.3 depicts the main categories, features, and nutritional value of snack bars.

1.3.4 Alkaline-Cooked Corn Products (Corn and Tortilla Chips)

The alkaline or lime-cooked corn products have positioned themselves as the second most relevant savory snack food category. These unique products evolved from the nixtamalization process widely employed by the early Mesoamerican cultures about 10,000 years ago when corn (*Zea mays*) became a cultivated plant and the chief responsible for the initiation of formal agriculture in Mesoamerica. According to Garcia-Lara and Serna-Saldivar (2019), the origin of this crop occurred during the invention of the new world agriculture. The oldest paleoetnobotanic evidence of its domestication is in an archeological site named "Nac Neish" located northeast of Mexico. It consists of three primitive caves presenting data between 6,000 and 20,000 years BC (Serna-Saldivar 2015, Garcia-Lara and Serna-Saldivar 2019). In one of the caves it was found a tomb that contained human remains covered with reed mats (*petlatl*) and an offering consisting of a basket with corncobs. The American Indians created corn from a tiny two-rowed ear of teosintle of about 3 cm long into the first tiny corn ear with its four ranks of paired female spikelets. This transformation took perhaps only 100–200 years. Thereafter, two different corns classified as pyramidal or cylindrical originated the modern corns widely planted throughout the globe. The oldest remains of 8 and 12 rowed corns from Mesoamerica are dated 7,200 and 3,000 years old, respectively. These relevant developments originated different races varying in kernel morphology, color, endosperm texture, and other important features that make these types highly useful for snack processors (white, yellow, blue, and purple corns for corn and tortilla chips, cacahuacintle for parched corn, popcorn, etc.). More than 25 races have been used to produce high-yielding varieties and hybrids that make corn the most productive crop in the planet with yearly production exceeding 1.1 billion tons (FAO 2021).

After the discovery of the Americas, the crop eventually reached and adapted to the Iberia Peninsula and from there it was distributed to other parts of the globe. The Portuguese conquistadors and merchants were more responsible than the Spaniards for disseminating corn around the rest of Europe and Africa. However, the Spaniards catalyzed the Asian connection because they traded goods from the Pacific ports of Mexico to the Philippines. This occurred as early as 1565 but maize became important in Asia after the 17th century.

The ancient Mesoamerican cultures not only inherited regular corn and popcorn to the whole world but also the nixtamalization process that is still used to produce corn and tortilla chips. Historically, it is known that the Aztecs produced *totopochtli*, an ancient prototype of free-fat tortilla chips, by toasting tortillas on a hot griddle known as *comal*. This shelf-stable product was carried as a snack by travelers or used as a substance during wars (Serna-Saldivar 2008b, Serna-Saldivar 2015).

The dramatic increase in sales of lime-cooked snacks occurred during the past 50 years is attributed to Latin Americans inhabiting the southwestern states of the United States. They first introduced fresh and toasted tortillas (tostadas) in the market and then the industry evolved by designing high output industrial lines aimed toward the production of deep-fat fried corn and tortilla chips.

The first use of industrial equipment to produce corn chips occurred in San Antonio Texas in 1932. Elmer Doolin, founder of the Frito Company, bought rights from a Mexican who wanted to

TABLE 1.3
Characteristics and Nutritional Value of the Different Categories of Snack Bars

Snack Bar Type	Formulation	Nutritional Value
Cereal-based	These bars are the most popular and the base for blending with other ingredients like proteins, other grains, flavorings/coverings, dehydrated, or moisture intermediate fruits and nuts. The main cereals used are flaked oats, wheat, expanded rice, and maize. The preferred raw materials are whole grains, refined cereal flours, starches, and puffed grains, which are normally blended with honey, syrups, caramel, and in many instances covered with chocolate or vanilla-based flavorings.	Most bars are high in starch and energy and have relatively low levels of protein unless bars are fortified with protein sources from soybean, pulses, or dairy products. The use of whole grains or flours yields products with more dietary fiber, micronutrients, and phytochemicals that prevent oxidative stress.
Energy bars 40-30-30	These bars are balanced to fall into the 40-30-30 of total calories provided by carbohydrates, protein, and fat, respectively. The development of these bars is based on the principles of the Zone diet. These bars are higher in protein and fat and lower in total dietary fiber compared to the higher carbohydrate cereal-based energy bars. The key for the production of these bars is the intelligent combination of cereals, pulses, pseudocereals, and oils to balance the composition of macronutrients. The principles of production of bars are similar to energy or cereal-based snack bars, which after blending and forming or molding the shelf-stable product is baked, cooled, and packaged.	From the nutritional and dietary viewpoint, the 40-30-30 caloric ratio is recommended by many dieticians because the energy and protein are well balanced and create satiety. Therefore, these bars are known to provide energy, good quality protein, and micronutrients that favor human health. The bars low in soluble sugars promote a slow glycemic response.
Protein-enriched	Most of these bars are produced by commingling cereal meals or flours with other grains rich in protein or protein flours, concentrates, and isolates. The most popular protein sources are soybean (nuggets, texturized vegetable protein, defatted flour, concentrate, or isolates), other legumes (flours, concentrates, peanut butter), and dairy products (casein and whey protein concentrate). The combination of cereal proteins with legumes or dairy proteins improves both the protein concentration and protein quality of finished products. In terms of processing, most high protein bars are produced by first mixing raw ingredients (cereal flours, puffed wheat, or rice), protein ingredients (soybean, pulses, whey protein concentrate, casein, nuts) with water, syrup, oils, chocolate chips, and minor ingredients like glycerine, hydrocolloids, emulsifiers, and flavorings. Then, bars are formed, molded, and baked. After cooling, some bars are coated to improve organoleptic properties. Within this category, there are organic and gluten-free products.	These bars may contain up to 35% protein, which is generally provided by the cereal base and the supplemented protein ingredients. When produced from whole grains the bars also supply important amounts of dietary fiber, vitamins, minerals, phytochemicals, and antioxidants.
Fruit-based	Fruit-based bars are increasing in popularity due to the positive image of dehydrated fruits. Generally, dehydrated fruit pastes or pieces with *Aw* below 0.8 are bending with honey, glucose, or fructose syrups and other ingredients like rice crisps, vegetable oil, glycerol, maltodextrins, and pectins. Products are usually obtained by forming or molding with special extruders and in some instances baked.	Fruit bars are high in sugar, energy, dietary fiber, micronutrients (vitamins and minerals) and phytochemicals including polyphenols and flavonoids Most fruit bars are low in protein.
Nut-based	Nut-based bars are also popular due to the positive image of roasted nuts obtained from peanuts (roasted pieces and peanut butter), soybeans, and different types of tree nuts. Generally, the nut pieces are blended with honey, caramel, glucose, or fructose syrups and refined or whole cereal flours, vegetable oil, glycerol, maltodextrins, and hydrocolloids. Products are usually obtained by forming or molding with special extruders and in most cases baked to partially dehydrate the product and improve the flavor profile. Within this category, there are vegan nut-based snack bars.	Nut-based snack bars are high in fat, protein, energy, dietary fiber, micronutrients (vitamins and minerals), and phytochemicals associated with whole grain flours and roasted nuts. Generally, the lipids contain a favorable polyunsaturated fatty acid composition that prevents cardiovascular diseases.

return to his homeland. Mr. Dooling started the business in his kitchen and soon sales boomed and within a year moved to Dallas. When Mr. Dooling passed away, he had transformed the 100 USD loan from his mother into an industry with yearly sales of more than 50 million USD (Serna-Saldivar 2015). I. J. Filler was granted a trademark for Corn Chips in Texas in the early 1930s. That is probably the reason why Mr. Dooling chose the name Fritos™. One of the major advances for the industrial production of corn chips was the development of a mechanical screw press developed by Mr. Doolin and the Lawson Brothers Machine Shop, which extruded the bulk of dough or masa into ribbons, which fell directly into the deep-fat fryer (Chapter 11). The machine consisted of a vertically positioned barrel and a mechanically driven piston that pushed the masa into the die located at the end of the barrel. When the piston retracted a new load of masa was put into the machine. This press was improved when the piston was driven by compressed air and a 90° elbow tube was fitted to the discharge end of the barrel. A cutter was also driven by a pneumatic assembly with an air regulator to control speed. These new extruders were capable of producing 200 kg/hr. Hydraulics machines widely used nowadays replaced the pneumatic systems. The advantages of these corn chip extruders were increased production and a more consistent and homogenous chip length. Frito-Lay/L. C. Miller Co. first built these extruders in the early 1960s (Snack Food Association 1987, Burtea 2001).

The most popular tortilla chips developed about 20 to 30 years later than corn chips. A. West and G. Chesquiere of the newly formed Frito-Lay Incorporation got the idea of producing tortilla chips after seeing Mexican-style tostadas and USA taco shells. The trade name Doritos™ was selected for these new snacks. The first triangular-shaped Doritos were manufactured at Alex Foods in Anaheim, California. The tests went so well that soon the products were not only produced in California but also in the southwestern United States. Doritos™ went to the national market in 1966. Few years later, sales of tortilla chips surpassed those of corn chips. J. C. Ford Company, Casa Herrera, Electra Food Machinery, Lawrence Equipment, Maddox Metal Works, and Heat and Control are the major suppliers of tortilla chip and frying equipment and automated lines. The larger production lines are capable of producing 1.5 tons of chips/hr (Serna-Saldivar 2008b).

Nixtamalized or lime-cooked snacks have experienced one of the most relevant growth rates in terms of volumes and sales during the past five decades and nowadays are manufactured practically in all developed countries of the globe (i.e., European countries, Russia, China, Australia, South Korea). In fact, the current market of tortillas chips has increased above the rate of potato chips so tortilla chips are expected to surpass the market and sales of potato chips within the next five years.

1.3.5 Extruded Snacks

Historically, it is well known that the extrusion technology was first developed to produce clay pipe, tile, and soap. In 1867, two Englishmen developed the first known twin extruder to process sausage but it was not until the mid-1930s that the single screw continuous pasta extruder was developed (Riaz 2000). The history of extruded snacks is also traced back to this decade. Corn chips were introduced in the early 1930s while puffed fried and baked products just after the Second World War. In the late 1920s, C. B. Mathews developed in Wisconsin the first prototype of an extruder that pulverized, macerated, and partially cooked animal feed with the aim of improving digestibility and reducing intestinal problems. He collaborated with H. W. Adams to improve the method, launched a company named Flakall Corporation, and issued a US patent in 1938. Ed Wilson, an operator from Flakall Corp, while cleaning the apparatus with corn noticed the formation of puffs. Instead of throwing the puffs, he asked his wife to deep-fat fry and salt the product. His neighbors liked the product especially when flavored with cheese and soon the product was locally produced and sold with the trade name *Korn Kurls*. A US patent was issued for the machine and process in 1939 and granted in 1942. In 1946, Harry Adams, owner of Adams Corporation, started to commercially produce the original fried type corn snacks. The key processing step was the extrusion. The extruder used consisted of a rotor, stator, and a screw that produced irregularly shaped collets ready for frying.

The fried collet was commonly seasoned with a salted-cheese oil slurry. C. Heigl, an engineer from Adams Corporation, developed an extruder designed to produce less dense extrudates and produce puffs suitable for drying or baking. The lighter and smoother collets were produced by a short barrel, high shear extruder equipped with a die to form the gelatinized corn extrudate into various configurations. Resulting puffs were cut to a predetermined length by a rotating knife. After drying or baking the collets were flavored with a cheese slurry similarly to the deep-fat fried curls (Burtea 2001, Serna-Saldivar 2008b). Later on, larger and more sophisticated extruders were designed and built by Maddox, Wenger, Buhler, and other companies. These extruders are very versatile because they can be arranged to produce second-generation expanded products or third-generation pellets (Chapter 12). A key and major advancement in the extrusion field was the manufacturing of twin extruders that improved versatility and product consistency and quality (Serna-Saldivar 2008b).

The 80-year-old extruded snacks segment is expected to witness considerable growth over the next five years driven by category diversification coupled with equipment and ingredient innovation, especially in developed countries. Frito-Lay the main snack food company of PepsiCo will continue to dominate sales of these snacks.

1.3.6 Snacks from Legumes and Pseudocereals

Legumes, pulses, and pseudocereals have been part of the diet of men since prehistoric times and involved with the development of agriculture. These grains provide many nutrients required by humans especially in terms of proteins, carbohydrates, dietary fiber, vitamins, and minerals. Basically, all legume seeds contain antinutritional factors (Chapter 20) that protect seeds against insects, animals, and other biotic elements. Therefore, men learn to process these grains in order to deactivate antinutritional factors like trypsin inhibitors, urease, and hemagglutinins. The simple toasting or cooking of whole seeds or meals deactivates these factors and greatly enhances their nutritional value. In terms of snacks derived from legumes and pseudocereals covered in Chapter 13, peanuts have been positioned as the most relevant and sold. Recently, the use of other legume seeds or meals like soybean nuts, soybean meals and proteins, chickpeas, and green/yellow peas are increasingly being supplemented with nutritional bars and other snacks.

1.3.6.1 Peanuts

Peanuts or groundnuts (*Arachis hypogaea*) originated in Brazil or Peru. Historically peanuts are known as early as 950 BC. Explorers and missionaries to Africa introduced them to Africa. From Africa they returned to the American Continent by slave traders in the early colonial days. In the United States, peanuts started to be demanded and consumed after the Civil War. The Italian native, Amedeo Obici, was the founder of the Planters Peanuts Company in the United States. He was born in 1876 near Venice, Italy, and when he was a teenager migrated to New York without speaking any English. He started his career as a bellhop and fruit stand vendor in Scraton, Pennsylvania, and later on moved to Wilkes-Barre, Pennsylvania, and opened a fruit stand and invested in a peanut roaster. In a few years, Obici using a horse and wagon successfully sold peanuts and named himself “The Peanut Specialist.” In 1906, Obici established a partnership with Mario Peruzzi and developed his own method of blanching whole roasted peanuts, doing away with the troublesome hulls and skins. Planters was founded, and soon the company was recognized as the benchmark in terms of quality and trade name (www.ideafinder.com/history/inventions/). In the year 1913, Amedeo Obici moved to Suffolk, Virginia, known for its peanuts, and then opened the first mass-production plant in this location. By the year 1930, Planters Peanut stores were open across the United States.

Nowadays, the Planters Company owned by Kraft Heinz processes and sells dry-roasted, honey-roasted, salted, non-salted, and hot peanuts. In 1998, Planters introduced the innovative product known as “trail mix” that evolved into an array of product blends with other nuts, granola, dehydrated fruits, chocolate candies, and other shelf-stable products that are viewed as healthy and convenient.

Another important historical development associated with peanuts and popcorn is the snack still known as Cracker Jack^{TM}. It consists of a unique mixture of popcorn, peanuts, and molasses first produced at the end of the 19th century by F. W. Rueckheim. This product was first commercialized at the World's Columbian Exposition at Chicago's First World Fair. Louis Rueckhein, brother and partner of the inventor, developed the process for keeping the molasses-covered popcorn morsels from sticking to each other (Serna-Saldivar 2008a).

1.3.7 Potato Chips

Potato chips are still the most consumed non-extruded snack in North America. Following a growing demand for potato chips across the region, a sizable number of market players are focusing on entering the tapping of the North American snacks market.

The potato (*Solanum tuberosum* L.) is indigenous to the Americas specifically the Andean Mountains of Peru, Ecuador, Bolivia, and Chile located in the western part of South America. Potatoes have been the staple of the inhabitants of these countries for more than 8,000 years (Gould 2001). Historically, the utilization of potato is traced to at least AD 200 where it was cultivated by the ancient Inca culture on the highlands of the Andes. The tubers were dried by allowing them to freeze overnight and thaw during the day. This cycle was repeated several times until lowering the moisture content enough to get a shelf-stable product. According to Gould (2001) and Talburt (1987), the Andean Indians mainly processed potatoes into dehydrated and convenient products named *Chuño* and *Tunta* used for the production of many indigenous foods. When the Spanish conquistadors arrived in the Americas, the wild potato crop was widely distributed throughout the continent. The Inca Indians cultivated potatoes intensively and were responsible for selecting a wide array of types varying in color (purple, pink, blue, yellow) and shape (round, oblong, cylindrical). Potatoes reached the Old World via ships that carried goods and people back to Europe. There are records that potatoes reached Sevilla, Spain, as early as 1573. From Spain, potatoes were carried to Italy and then disseminated throughout the rest of the old continent. Potatoes reached England at the end of the 16th century and soon were adopted as a staple by the Irish people. By the 18th and 19th centuries, the potato crop became the staple food in Europe, especially in the eastern countries. Interestingly, the North Americans introduced the crop via Irish settlers approximately in 1621 instead of obtaining the crop earlier from natives inhabiting the areas of New Mexico and Arizona. The Irish settlers of New Hampshire promoted the cultivation and acceptance of the potato crop.

In order to prolong the potato shelf-life and decrease its bulk the first documented production of potato meal was in 1786 whereas the first potato starch plant was created approximately 45 years later (Talburt 1987). The first potato chips were manufactured in 1853 by a New York chef named George Crum who was trying to develop a thinner version of French fries. The elegant restaurant menu included French fries prepared by Crum in the standard thick-cut French style that was popularized in France in the 1700s and enjoyed by Thomas Jefferson as ambassador to that country. Ever since Jefferson brought the recipe to America and served French fries to guests at Monticello. One guest found Chef Crum's fries too thick for his liking and rejected the order. Crum cut and fried a thinner batch, but these also were disapproved. Exasperated, Crum decided to rile the guest by producing fries too thin and crisp to skewer with a fork. The plan backfired because the guest was ecstatic over the first known prototype of potato chips. Since then paper-thin potato chips appeared on the menu as a house specialty. Soon chips were packaged and sold first locally then throughout the New England area and then disseminated to other parts of the United States. The invention of the mechanical potato peeler in the 1920s paved the road for potato chips to roar from a specialty item to a top-selling savory snack thoroughly described in Chapter 14. For several decades after their creation, potato chips were largely sold in Northern United States. In the 1920s Herman Lay was mainly responsible for popularizing potato chips in the southeast part of the United States. At the beginning of the 1960s he merged with Frito-Lay expanding even more volume sales (www.ideafinder.com/history/inventions/).

1.3.8 Almonds and Tree Nuts

The consumption of nuts probably dated back to the origin of the human species when men were tree dwellers and fruit gatherers and developed tools and skills to crush or break the hard shells of tree nuts. These products were preferred due to the high energy density and nutritional value.

The different types of tree nuts originated in diverse regions around the globe (Chapter 15). Almonds (*Amygdalus communis*), cashew (*Anacardium accidentale*), and macadamia (*Macadamia integrifolia*) trees originated in the Mediterranean, Brazil, and Australia, respectively. The first Macadamia plantations occurred in 1878 in the Hawaiian Islands. The Persian walnut (*Juglans regia L*) suggests Iraq as its native homeland but its original distribution was larger and extended from the Caucasus to Turkestan. On the other hand, walnuts were known to the ancient Greeks and from Europe reached North America with the early settlers during the 16th and 17th centuries. The term English walnut is also used because these nuts were transported in English ships.

The pecan tree (*Carya illinoensis*) is native to America. The pecan nuts were used for food for thousands of years before the discovery of the continent in 1492. The Spanish conquistador Hernan Cortes saw this indigenous tree during his journey to Tenochtitlan (today Mexico City). Lope de Oviedo, a member of the Spanish expedition, described for the first time in his journal the American pecan nut and described it as a much smaller nut compared to those commonly grown in Spain (walnut). In 1541, Cabeza de Vaca, a Spanish nobleman and treasurer, also wrote about pecans and mentioned that it was a subsistence crop for at least two months every other year for native Indians. The pecan name was adopted from the Algonquin Indian tribe language meaning that nuts were so hard that needed a stone for cracking. According to Brison (1974), the commercial pecan industry started about 1880. Therefore, the pecan industry is relatively new compared to other orchard crops.

The almond and tree nuts snack market is expected to observe significant demand in the upcoming years especially among millennials. The expected growth is due to their plant base nature and nutritional value in terms of protein, fatty acid profile, and micronutrients, which make them suitable for the surging market of organic/healthy snacks.

1.3.9 Fruits and Vegetables

Dehydrated fruits and vegetables initially obtained by solar drying have a long tradition of use dating back to the fourth millennium BC in the Middle Eastern region known as the Fertile Crescent where Mesopotamia (Iraq), Iran, southwest Turkey, Syria, Lebanon, and Israel are located. The earliest records of desiccated fruits can be found in Mesopotamian tablets dating to about 1500 BC, which depicted dietary patterns with fruits such as grapes, dates, figs, pomegranates, and apples. These early civilizations used dates, date juice evaporated into syrup, and raisins as sweeteners. They also included dried fruits in their breads for which they had more than 300 recipes. From the Fertile Crescent region, these fruits spread through Greece and Italy where they readily became a major part of the diet. The ancient Romans consumed raisins in impressive quantities and raisins-supplemented breads were part of the common diet. (https://en.wikipedia.org/wiki/Dried_fruit#History). The removal of most of the moisture associated with fruits and vegetables with the concomitant concentration of soluble carbohydrates is key to lower the *Aw* to levels which avoid the growth of bacteria, yeasts, and molds.

The intentional drying of raisins, dates, other fruits, and vegetables was practiced in order to prolong the shelf-life of these items without losing nutritional attributes and were fundamental for the prevention of scurvy among mariners that stayed long times offshore. There are several European and US documents that clearly depict the production of desiccated vegetables and the usefulness of these products to prevent scurvy and other nutrient deficiencies. As a result, The American Desiccating Company of New York was established in the middle of the 18th century.

Nowadays the consumption of dried fruits and vegetables is still widely practiced around the globe. Approximately half of the dried fruits produced today are raisins, followed by dates, prunes, figs, peaches, apricots, pears, mango, and apples (Chapter 16). During the past decades, high antioxidant fruits like blueberries, cranberries, and strawberries have gained market especially in the form of osmotic-dehydrated items (Chapter 16) offered in blends and nutritional bars.

1.3.10 Milk-Based Snacks

Humans have consumed dairy products from cows, sheep, and goats for at least 10,000 years. Archaeological evidence from the Neolithic revolution (8000 BC) points out the use of milk first in the Middle East and later on in regions of Europe and Africa. It is documented that 10,000 to 11,000 years ago goats were the first milk-producing domesticated mammals used by ancient cultures whereas cows were domesticated in eastern Sahara no later than 9,000 years ago. The emergence of dairying was a major innovation in prehistoric societies, enabling the supply of nutritious food without the slaughtering of prized livestock

The processing of milk into cheese and fermented products similar to yogurt would have been a critical development because it not only allowed the preservation of dairy products in a nonperishable and transportable form but also made milk a more digestible commodity for early prehistoric farmers. The key for the processing of these items is the natural fermentation of milk by lactic acid bacteria and the addition of salt to cheeses.

The first unequivocal evidence that humans in prehistoric Northern Europe made cheese more than 7,000 years ago is described by Salque et al. (2013) who found remains of fatty acids in pottery or cheese strainers especially made to produce the first prototypes of cheeses. The earliest perforated pottery sieves dated between 5200 and 4800 BC were found in the Linerbandkeramilk territory located in the strip of Hungary, Germany, Poland, France, Netherlands, and Ukraine/Russia (https://www.thoughtco.com/dairy-farming-ancient-history-171199).

Yogurt is also considered one of the oldest dairy foods produced by mankind. Most historians place its discovery somewhere between 9000 and 6000 BC in Central Asia (Mongolia Region) where men domesticated mares, cows, and camels. The history of the first fermented milk or yogurt goes back to Neolithic times when animal herders stored milk in the intestines of cows. Bacteria found in the intestines grew in the milk-yielding and acidic dairy product rich in probiotic bacteria. Then, the first fermented yogurts spread to the Middle East and Europe, and throughout the world. Yogurt is depicted in many old documents including the ancient Indian Ayurvedic scripts, the Bible, and historic texts. The great Mongol warrior and conquistador Genghis Khan is documented to have encouraged the drinking of fermented horse milk yogurt, known as *kumis*, to his warriors in order to maintain them healthy and brave. The Russian scientist Elie Metchnikoff was the first to record the health benefits of cultured milk on Bulgarian people and credited as the first one to indicate that the bacteria in fermented milk helped to diminish the amount of prejudicial bacteria in the gastrointestinal tract. His findings influenced the founder of the company Dannon Isaac Carasso to develop commercial products including yogurt supplemented with fruits. The expansion of yogurt sales started in the middle of the 20th century especially in the United States and Europe (http://www.indepthinfo.com/yogurt/history.htm).

1.3.11 Meat- and Marine-Based Snacks

Fresh meat, fish, and crustaceans rapidly deteriorate due to their high moisture and *Aw* contents. The use of sun-drying or camp fire-drying allowed primitive nomad races to desiccate meats for traveling and safe-keeping for future utilization. This easy-to-perform practice was key for the keeping of large game meats that otherwise rapidly deteriorate. The Egyptians made jerky from animal meat that was too big to eat all at once. Archeologists have found remnants of dried meat in Egyptian tombs dated 3200 BC.

The art of preservation by drying was not isolated to the African and European continents. In the Quechuan language of the Incas, the word *ch'arki* means dried meat. This product of the Andes was made of alpaca and llama meat debonded, pounded, and dehydrated in the arid climate of South America. The indigenous people shared this food with Spanish conquistadors who took the concept back to Europe. The Quechua word eventually evolved to jerky (https://delishably.com/meat-dishes/Exploring-Jerky-History-of-Preserving-Meat-Around-the-World#). Likewise, it is documented that the North American Indians mixed ground dried meat with dried fruits to make *pemmican*.

Practically all prehistoric cultures learn that the drying/smoking practice was key for their subsistence because it concentrated the meat nutrients while keeping the main nutritional attributes. The dehydration process evolved when meat and fish products were salted. Salting allowed a faster dehydration and significantly reduced microbial contamination especially during the first stage of drying. Men soon realized that the use of common salt contaminated with nitrates (Chapter 18) or pepper salt allowed the production of more stable products with a different flavor profile. This practice initiated the generation of dry-cured products. The nitrate salts avoid the growth of most pathogenic bacteria and practically assure the production of pathogen-free products (Chapter 18).

The use of freeze-drying or lyophilization was developed during the 20th century in order to improve the properties of dehydrated products. Freeze-drying removes the water by sublimation from the frozen meat. Freeze-dried products have a better texture, rehydration capacity, taste, color, and overall acceptability when compared with conventionally dehydrated counterparts. However, the excessive processing cost and the lack of continuous high output freeze-driers limit the use of this technology. Nowadays, the quantity of meat and seafood products processed by drying remains relatively small in comparison with the amounts of products consumed fresh, cured, or canned. However, the recent interest in low carbohydrate and keto diets and snacks rich in protein and other nutrients have gradually increased the demand for dehydrated animal-based snacks.

Fishing is a prehistoric practice dating back at least 40,000 years and is responsible for enriching the diet of our ancestors. Isotopic analysis of the skeleton of a 40,000-year-old modern human from eastern Asia has shown that he regularly consumed freshwater fish. Archaeological evidence of discarded fish bones and cave paintings show that seafoods were relevant for the survival of many ancient cultures. The Egyptians invented various implements and methods for fishing and these are clearly depicted in tomb scenes, drawings, and papyrus documents.

There is evidence of dehydration of fish and poultry meats 12,000 years BC by the ancient Egyptian culture. The drying operation of different types of fish evolved when products were assisted with salting and smoking. These three practices act synergistically to inhibit and prevent both the growth of spoilage and pathogenic microorganisms. Historically, the combination of salting and drying of cod has been practiced for at least five centuries. Desiccated fish has been a common snack and staple in Nordic cultures for centuries. The preferred species are white fish, usually cod or haddock, dried on wooden racks in the open air.

The simple solar drying technique used until the Middle Ages evolved when the Europeans constructed special structures, known as stillhouses, specifically designed to dehydrate foods via the heat generated by a fire.

1.4 STATISTICS OF SNACK FOOD PRODUCTION, SALES, AND CONSUMPTION

According to the global market of snack foods is approximately 520 billion USD in 2020 and expected to grow to more than 700 billion USD by 2025 (https://mordorintelligence.com/industry-reports/snack-food-market). Table 1.4 summarizes the global sales of the main sorts of snacks in the year 2018. The market is expected to grow at a compound annual growth rate of 6.2% from 2019 to 2025. The current market is dominated by nonextruded snacks because the consumer is demanding healthy products, such as granola and fruit bars, nuts, and high-protein low-carbohydrate items for special dietary regimes and prevent noncommunicable or chronic diseases like cardiovascular, hypercholesterolemia, and diabetes that are currently responsible for about 65% of the deaths.

The overall snack market in the United States, which comprises nonextruded and extruded snacks, exceeded 125 billion USD in 2019 and is expected to grow to 175 billion by the year 2025.

TABLE 1.4
Global Sales of the Main Types of Snacks in the Year 2018

Type of Product	Sales Billion USD (2018)
Chocolate/confectionary	110
Salty snacks	83
Ice cream	77
Sweet biscuits	73
Nuts, seeds, and trail mixes	27
Savory biscuits	23
Other savory snacks	18
Dairy and frozen desserts	15
Snack bars	14
Fruit snacks	11
Popcorn	5
Pretzels	3

Source: Chung (2019).

Nonextruded and extruded snacks represent about 85% and 15% of the current US market (www.grandviewresearch.com) and the salty snack category is expected to reach 109 billion USD by 2025. The savory snack food market in the United States estimated at 42 billion USD has grown since 2014 at an average annual rate of 1.4%. In this country, there are about 3,700 active businesses involved in the manufacturing of the different types of snacks providing employment opportunities for approximately 62,000 people. (IBIS World).

According to the packaging world, the global market for healthy snacks was worth 21.1 billion USD in 2016. The fruit snacks, nuts, and seeds accounted for approximately 25% of the market share in this particular category. Likewise, protein snacks are a significant driver for purchases in the snack food industry today. This category was up 6.6% from the year before, with some products that experienced 582% revenue growth in 2017 (IRI Market Advantage).

In the year 2018, the Americans, Netherlanders, Estonians, Canadians, and South Koreans had the highest annual *per capita* consumption of snack foods with an average annual intake of 22.4, 9.1, 8.7, 8.3, and 9.1 kg, respectively (Figure 1.1).

In 2019, the main companies that fabricated snacks and bakery items with yearly sales exceeding 10 billion USD were Nestle, PepsiCo, Mars, Mondelez International, Kraft-Heinz Co, General Mills, Kellogs, Ferrero, and the Mexican group of Bimbo. These nine companies sold nearly 310 billion USD (Table 1.5, Peckenpaugh 2020). Among savory snacks, potato and tortilla chips are the two most popular in terms of volume and sales. Frito-Lay North America accounts for 25% of the revenue at PepsiCo and is the leading producer of savory snack foods in the US market.

Retail sales of savory snacks in the United States projected to the year 2022 are expected to exceed 55.3 billion USD (Wunsch 2020). According to Mintel (Anonymous 2015) 95% and 50% of all Americans snack once and two to three times a day. The Americans also claim a preference for healthier snacking with 33% saying they are snacking with healthier foods specially formulated with simple ingredients and low-energy contents. However, 62% most often snack to satisfy a craving, highlighting the relevant role of taste. In fact, 63% of US consumers value the taste of salty snacks more than their nutrition. Importantly, the millennials are more likely to snack compared to older generations as a means to fulfill emotional and functional needs and added nutrition. As a result, they may be drawn to products with high fiber, energizing claims, or protein content to stay

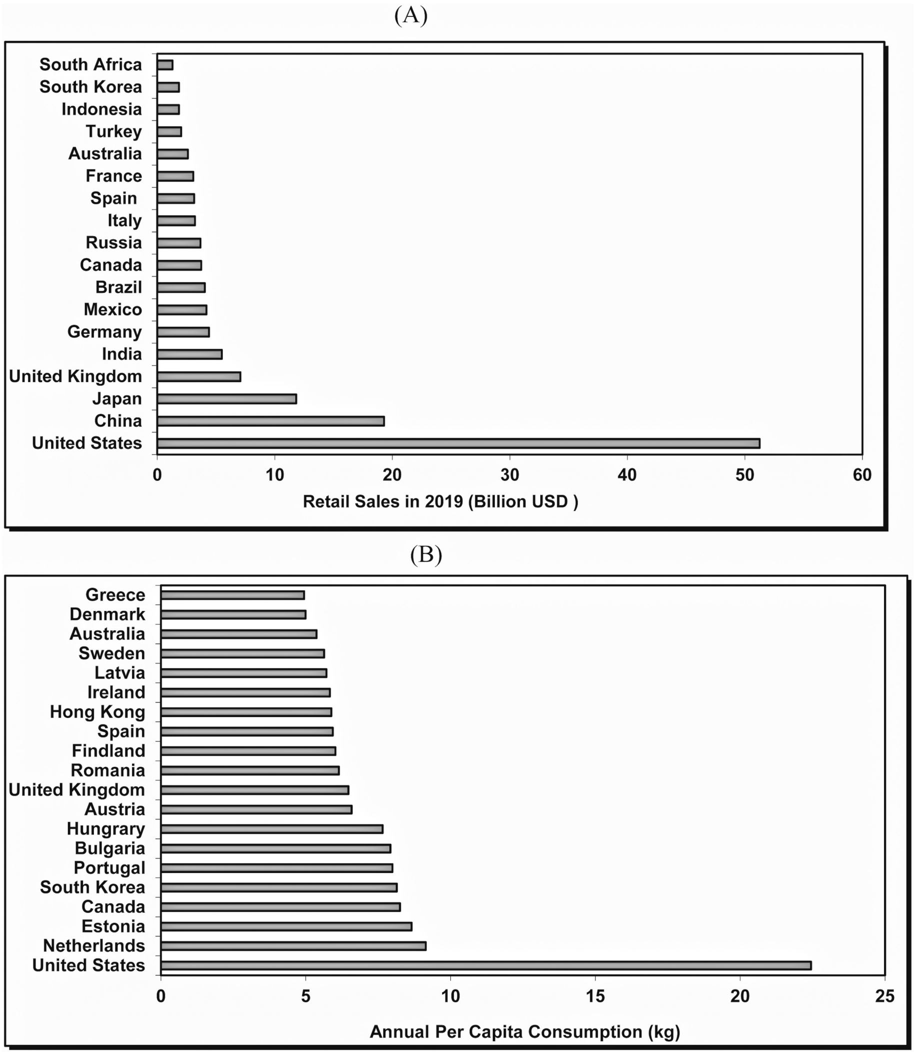

FIGURE 1.1 (A) Retail sales of savory snacks and (B) *per capita* volume consumption of snack foods in the leading countries of the world.

satiated, as well as bold flavors to help add variety to their frequent snacking occasions and eliminate boredom (Anonymous 2015).

North America and Western Europe are currently the largest snack markets, accounting for nearly 50%. According to Driscoll, the developed markets represent about 60% of total sales, while emerging markets represent the remaining 40%. Snacking in emerging markets has grown at a 7.3% compound annual growth rate over the past five years, three times faster than in developed markets (Chung 2019).

According to a contemporary survey performed by Datamonitor in Europe, the Britons munch their way through four times as many snacks a year as their Spanish cousins. In the snacking stake, in which they each shell out an average £204 a year on snack items. British consumers are situated far ahead of their nearest rivals in Sweden and the Netherlands. Residents of those countries spent £166 and £165, respectively, followed by the Germans who consumed £162 worth and the French £146. Taste was noted as the most influential factor on snack food product choice with consumers unwilling to compromise in exchange for added health benefits. Findings suggest new food product

TABLE 1.5
Top 20 Snack and Bakery Companies of the World in the Year 2019

Ranking	Company	Sales Billion USD (2019)
1	Nestle S.A.	101.5
2	PepsiCo	67.2
3	Mars, Inc.	35.0
4	Mondelēz International	25.9
5	Kraft Heinz Co.	25.0
6	General Mills	16.9
7	Kellogg Co.	13.6
8	Ferrero	12.6
9	Grupo Bimbo S.A.B. de C.V.	12.1
10	Conagra Brands	9.5
11	Arca Continental S.A.B. de C.V.	8.8
12	Campbell Soup Co.	8.1
13	The Hershey Co.	8.0
14	The Wonderful Co.	6.7
15	Post Holdings	5.7
16	TreeHouse Foods	4.3
17	Flowers Foods	4.1
18	Rich Products Corp.	4.0
19	ARYZTA	3.7
20	Premium Brands Holding Corp.	3.6

Source: Peckenpaugh (2020).

development in the UK market will continue to focus on the convenience and comfort from eating while on the move.

1.5 NUTRITIONAL VALUE OF SNACKS

In general, snacks are categorized as empty foods because they contain a high amount of fats/oils and sodium and most contain low protein and essential amino acids. The dietary fiber, vitamin, mineral, protein content, and protein quality of most snacks are low because they are generally manufactured from refined cereal grits and/or starches. The nutritional value of snacks discussed in Chapter 20, highly depends on the amount of fat absorbed during the frying process or added as flavoring base. Snacks are one of the highest energy-dense foods available because they practically do not contain water and are rich in fats which provide 9 kcal/g. The higher the oil content the lesser the amount of essential micronutrients such as vitamins and minerals. The issue of *trans* fatty acids present in partially hydrogenated frying oils and shortenings still used by many snack processors has further damaged the image of this particular industry.

Other major drawback of cereal-based snacks is that they contain low quantities of protein and more importantly the protein lacks lysine. Most snacks are salted or flavored with salt-based flavorings therefore these products commonly contain large quantities of sodium, which is related to hypertension and cardiovascular disease (Chapter 21). This essential electrolyte is considered the single nutrient most abused by modern humans because an average diet usually provides at least ten times the recommended daily intake. For these multiple reasons, snacks are viewed as “empty foods” and have a bad image among dietitians and health practitioners.

Among snacks, popcorn, peanuts, and other legumes or pseudocereals, almonds and tress nuts are gaining popularity because they are viewed as natural and nutritious. These products are rich in dietary fiber and also contain significant amounts of micronutrients and phytochemicals (Chapter 21).

Among cereal-based snacks, popcorn (Chapter 9) is considered one of the best nutritionally recommended because it is rich in starch, dietary fiber, and B-vitamins (Table 1.1). Likewise, the wheat-based hard pretzels, crispbreads, pita chips, and biscuits or crackers discussed in Chapter 10 are relatively lower in calories compared to other snacks. The nutritional value of these products resembles more bakery products than snacks (Chapter 20). The chief difference is that since these products are low in moisture they are usually more energy dense than soft bakery counterparts (Table 1.1).

Corn and tortilla chips produced with the nixtamalization process (Chapter 11) are considered energy-dense snacks because they mainly constitute starch and oil. These snacks are rich in sodium and lack good quality protein due to the deficiency of the essential amino acids lysine and tryptophan. However, they contain adequate levels of calcium and B-vitamins (Chapter 20) and their nutritional value is improved when combined with other legume seeds and vegetable proteins. Corn chips are more energy dense compared to tortilla chips, they normally contain 36 and 24% oil, respectively.

Most second- and third-generation extruded snacks (Table 1.2) are normally produced from refined cereal fractions practically devoid of vitamins, minerals, and dietary fiber and are obtained after various heat treatments that compromise even more the bioavailability of relevant vitamins. Most extruded snacks covered in Chapter 12 are considered as high caloric and empty foods and mainly constitute starch and oil (Chapter 20).

The acceptance of legume nuts, almonds, and tree nuts has increased recently because many epidemiological and clinical studies have shown that consumption of these items are associated with reduced risk of cardiovascular diseases because they contain high amounts of proteins, complex carbohydrates, polyunsaturated fats, both liposoluble and hydrosoluble vitamins, and antioxidants. These raw materials are blended with dehydrated fruits, concentrated forms of vegetable proteins, and sweeteners for the manufacturing of many new nutritional bars.

Likewise, the popularity of dehydrated fruits and/or vegetable-based snacks has increased because of their low oil content and high dietary fiber, micronutrient composition, and antioxidants.

Potato chips, which are still considered the most popular savory snack across the globe, are highly caloric because of their high starch and oil contents that provide more than 500 kcal/100 g serving. These snacks are usually devoid of dietary fiber, protein, and micronutrients and can contain relevant amounts of the potentially carcinogenic compound of acrylamide (Chapter 20).

Dairy and meat-based snacks contain more protein and the protein is much better in terms of essential amino acid balance. The consumption of meat/poultry/fish/crustaceans and milk-based snacks discussed in Chapters 17 and 18 are also gradually gaining market especially among consumers who would like to adopt a low-carbohydrate and high-protein diets (Table 1.1).

Nowadays, food scientists are including in their research and product development equations on the production of snacks with minimal fat calories and fat decomposition products known to have adverse effects on human health and produce snacks with similar organoleptic properties (flavor, texture, and overall acceptability) compared to regular counterparts. A healthful balance of fatty acids (saturated:monounsaturated:polyunsaturated and omega 6:omega 3) and the production of snacks free of *trans* fatty acids are into consideration.

The image of snacks has worsened because of the higher indexes of overweight and obesity in people inhabiting developed countries around the world. All chronic diseases (hypercholesterolemia, hyperlipidemia, cardiovascular disease, diabetes, hypertension, and cancer) are highly correlated with the body mass index and overconsumption of calories (Chapter 21). In order to overcome the bad reputation, the industry faces big challenges such as the production of low-calorie, high-fiber, and high protein items and snacks produced from natural products like whole grains high in nutraceuticals that diminish the incidence of noncommunicable diseases. In order to be successful in the market, new products should combine excellent organoleptic properties, high nutritional value, shelf-life, convenience, and marketing strategies.

1.6 MAJOR CONSTRAINTS OF SNACKS

The snack food industry faces important challenges in the near future. The first and most important is to reverse the bad image as producers of junk foods rich in calories, fat, and sodium and low in essential micronutrients and phytochemicals. In addition, processors should produce products that meet the minimum standards in terms of mycotoxins, microbial counts, trans fats, and toxic compounds like acrylamide and nitrosamines.

1.6.1 Major Nutritional and Health Concerns

As mentioned earlier most snacks as viewed as junk foods and processors should adapt products and processes in order to overcome the major constraints of new customers. Undoubtedly, the major goals should be to lower the amounts of calories, sodium, soluble sugars, trans fats, saturated fats, and cholesterol and increase levels of both insoluble and soluble and prebiotic dietary fiber, proteins, micronutrients, and phytonutrients so to produce novel products with enhanced nutritional value and health-promoting properties. In addition, processors should modify processing conditions in order to minimize the loss of important nutrients and the generation of harmful and toxic compounds.

1.6.2 Potential Toxicological Compounds

One of the main constraints of snack foods is related to public health in terms of affecting the health of consumers via pathogenic bacteria, toxigenic molds, and several toxic chemical compounds generated during deep-fat frying.

1.6.2.1 Pathogenic Bacteria

There are several categories of snack foods that might cause food-borne illnesses due to cross-contamination with pathogenic bacteria, although generally speaking these products rarely pose public health hazards due to their low moisture and *Aw*. The two most susceptible categories are snacks derived from meat/fish/crustacean and dairy products (Table 1.1) that are not thermally treated at temperatures that inactivate pathogenic microorganisms. These products that are increasingly being consumed due to their high nutrition profiles should be processed to meet the maximum allowed populations of pathogenic bacteria usually assessed by coliform counts. The most important pathogenic bacteria that are known to cause serious food-borne illnesses and even in some cases death are *Listeria*, *Salmonella*, *Clostridium*, *Shigella*, and *Vibrio*. These important bacteria can be also controlled with dehydration, use of curing salt, supplementation of fermenting microorganisms like lactic acid bacteria and yeast, and the intentional addition of organic acids and preservatives like propionates, sorbates, or benzoates.

1.6.2.2 Mycotoxins

Snacks based on peanuts, corn, and tree nuts might contain significant amounts of mycotoxins that can have acute and chronic toxicological effects. Unfortunately, most mycotoxins are heat resistant and therefore persist in finished snacks. Corn, peanuts, and tree nuts are susceptible to contamination to different mycotoxicogenic molds belonging to the *Aspergillus* and *Fusarium* genus when stored at relatively higher moistures of *Aws*. The most relevant and worrisome mycotoxins are aflatoxins, ochratoxins, and fumonisins that are known to cause cancer, neurological disorders, renal failure, and suppression of the immune system. In nature, aflatoxins are considered among the most powerful hepatocarcinogenic agents and most regulatory agencies regulate maximum permitted levels in foods (Generally < than 20 ppb or 0.02 ppm). These toxic compounds can be generated at the field and during faulty storage. The processes of dry milling for the production of refined fractions and nixtamalization or lime-cooking for the production of corn and tortilla chips are known to significantly reduce mycotoxins.

1.6.2.3 Toxic Compounds from Degraded Oil

One of the major public health concerns of the snack industry is related to toxicogenic compounds generated during frying and lipid oxidation. These main documented harmful reactions are autoxidation at temperatures higher than 100°C, polymerization in the absence of oxygen at temperatures ranging from 200 to 300°C, and thermic oxidation reactions at 200°C. According to Hosseini et al. (2016) approximately 400 types of decomposition products have been identified in fried products although about 50 are potentially carcinogenic. These compounds are additionally known as mutagenic, hyperlipidemic, and cholesterolemic, increasing the risk of cardiovascular diseases. The most relevant and worrisome toxic compounds are acrylamide, cyclic fatty acid monomers, aldehydes, acrolein, heterocyclic aromatic amines (HAA), and polycyclic aromatic hydrocarbons (PAH) discussed in Chapter 20 (Tareke et al. 2000, Mucci et al. 2003, Kim et al. 2005, Romero et al. 2000, Hosseini et al. 2016). For instance, the mutagenic potency of HAA is about 100-fold stronger than that of aflatoxins. As a result, the industry has focused on diminishing the formation and concentration of these harmful compounds in finished products. Several research fronts around the globe have investigated the use of additives or novel frying technologies to minimize the generation of these toxic compounds.

1.7 FUTURE OUTLOOK

The main elements driving the global snack food market include the growing trend of nuclear families, the adoption of Western eating habits among residents in emerging countries, busy lifestyles, diversity of snacks even within categories, and convenience. The increasing number of companies and the prompt influx of novel products in the market have enhanced consumer interest. The market is expected to witness healthy growth especially in developing countries where higher population growth is expected. The forecast of population growth in the next 30 years clearly indicates that the world will have approximately between 2 and 2.5 more billion people. The industry should adapt to these challenges by developing and launching new and innovative snacks with improved nutritional profiles and green labels in terms of usage of natural and GRAS ingredients to favor nutrition, health, and quality of life.

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2 Application of Traditional and Emerging Processes

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CONTENTS

2.1 INTRODUCTION

One of the most relevant food sectors within the ready-to-eat (RTE) category is the snack industry. This industrial sector began its development in the United States at the end of the 19th century, using cereals as the main ingredient. Nowadays, snack processing is still an important field within the food industry (Fast 1999). Several snack classifications depend on the feedstock and the manufacturing process (Chapter 1). Some snack-type foods are raw cut vegetables, potato-based products, corn-based products, half products or pellets, directly expanded extruded snacks, and corn pops, among others (Guy 2001). The elaboration of traditional snacks has three generalized

DOI: 10.1201/9781003129066-2

steps: (i) the first step implies the hydration of starch so that the formed dough can be manipulated; (ii) the next step includes the application of high temperatures to heat the dough, in this operation moisture is liberated as vapor from the inside of the material, resulting in the product expansion; (iii) finally, there is a drying step to remove the moisture excess, leaving a food product with low moisture content and with the desired sensory attributes, such as crispiness and flavor. In the second stage, the dough heating must be conducted with a fast temperature increment to a temperature that normally exceeds the boiling point. After reaching this temperature level, most of the water boils simultaneously and is released from the dough. This unit operation can be performed using several technologies such as extrusion, frying, drying, and baking. On the other hand, the selection of the manufacturing technology and the process variables are crucial to obtain the desirable sensory characteristics of these types of products.

This chapter first reviews some of the fundamental principles of the traditional processes used for the preparation and processing of various types of snacks and second covers some new ingredients and emerging technologies that are being increasingly adopted to improve processes and generate novel types of snacks.

2.2 TRADITIONAL PROCESSES APPLIED TO SNACK PRODUCTION

The following sections will cover mainly the processing conditions and currently used equipment for traditional processes employed by snack processors. In his chapter, the importance of extrusion is covered although the various types of extrusion processes used for snack production would be thoroughly studied in Chapter 12. A brief description of the principles of the process is described, while the focus of this section is the modification in the composition of fiber due to the thermoplastic process and its importance on the development of novel ingredients to improve the nutritional quality of snacks.

2.2.1 Extrusion

2.2.1.1 Principles of the Extrusion Process/Traditional Processes

Extrusion cooking is one of the most used technologies to produce snacks. In this process deeply described in Chapter 12, the raw material is converted into a food product through an efficient, rapid, and continuous operation. Food extruders are considered an efficient manufacturing equipment due to the thermic and mechanical energy produced to cause physicochemical modifications of the raw materials, resulting in complete homogenization of the extruded ingredients (Anton et al. 2009). This technology includes several unit operations, such as mixing, forming, texturizing, cooking, cutting, puffing, and drying, which occur almost simultaneously (Sumathi et al. 2007). The use of extrusion has continuously increased in the last 40 years to produce foods and food ingredients, mainly snacks, RTE breakfast cereals, baby foods, baking goods, supplementary foods, meat and cheese analogs, modified starch, among others (Ding et al. 2006, Shah et al. 2021). In its origins, an extruder basically formed by a rotor, stator, and a screw was used to produce an uncooked material that needed a subsequent frying process. Nevertheless, newer extruders designs constituted by a short-barrel and/or a high-shear mechanism with a plate die, allow the production of less dense materials suitable for drying or toasting (Serna-Saldivar 2010). Today, the extrusion process is characterized by a rapid heating process and by the formation of an extrudate in a relatively short time. The extrudates emerge from the die with high expansion rates (Bredie et al. 1998, Harper 2019).

The conditions necessary to maintain extruded products with a vitreous structure are the low moisture and the temperature. Usually, a food with moisture lower than 5% $_{(}$wb$_{)}$ preserves its crispy texture at no more than 40°C. After this temperature, the food changes into a plastic or viscoelastic material (Guy 2001). During the extrusion process, there are high temperature and humidity conditions, which generally result in several reactions that produce colors and aromas, such as Maillard reaction, lipids and vitamin degradation, and Strecker degradation of amino acids. However, due to the short residence time of the material inside the extruder and the rapid cooling of the extruded food emerged from the extruder die, several compounds responsible for those reactions are immobilized within the vitreous structure of the food (Bredie et al. 1998). For this reason, the adequate control of the process variables can enhance the production of desirable aromas in the food products, making the extrusion process a superior technology to produce snack foods.

Twin-screw extruders to produce snacks have been more extensively used mainly due to the capacity of this technology to create a great variety of shapes, textures, and even flavors. The barrel temperature, the melt's moisture, and the shear produced by the two screws are essential variables of the process that modify the characteristics and final quality of the product. The expansion of the melt in snacks occurs mainly when it emerges from the die or orifice and depends primarily on two mechanisms: (i) one is known as the die swell phenomenon, where the volume increment occurs by the pressure differential between the internal matrix inside the die with the outside pressure; and (ii) the expansion produced by the sudden evaporation of water within the melt, where small bubbles are made in a process known as nucleation. The former mechanism is considered more relevant in foods. The bubbles enlarge their volume depending on the extensional viscosity of the food matrix (Figure 2.1) (Fan et al. 1994, Pai et al. 2009). Both phenomena depend on both the transition temperature of the extruded materials and the shear and extensional rheological properties of the melt (Blake 2006).

The quality and the functional properties of the extruded snacks depend on the composition and features of the raw ingredients especially in terms of moisture content, water absorption index, starch, and dietary fiber properties, fat content, particle size, and the hardness of grains or their dry-milled fractions. From the processing viewpoint, the screw(s) configuration, screw speed, feed rate, conditioning water, die shape and diameter, and heating rate are of paramount importance. Furthermore, the operational variables like residence time within the barrel, temperature, and pressure profile in the barrel's sections affect shear and specific mechanical energy produced by the screws (Brennan et al. 2013).

The raw material typically utilized for the production of extruded snacks are dehulled grains or refined flours with a high starch content, therefore, with a low content of phytochemicals and dietary fiber. Refined fractions are preferred because of their higher content of starch that enhances functionality in snacks and ready-to-eat foods. Extrusion may be used to cook, form, and expand materials known as directly expanded snacks, which are ready-to-eat products; however, this technology can yield pellets or half products used for the production of third-generation snacks (Chapter 12). Half products are known to be compact or dense materials that need an additional unit operation, basically frying, to produce the expansion and desired characteristics in finished products (Serna-Saldivar 2010). The diagram flow depicted in Figure 2.2 shows the basic process to produce both directly expanded and third-generation extruded snacks.

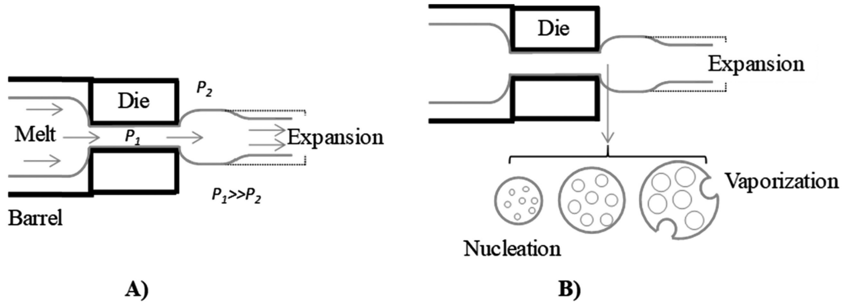


FIGURE 2.1 Phenomena involved in the expansion process during extrusion. (A) Die swell phenomenon and (B) vaporization of water in the extruded matrix.

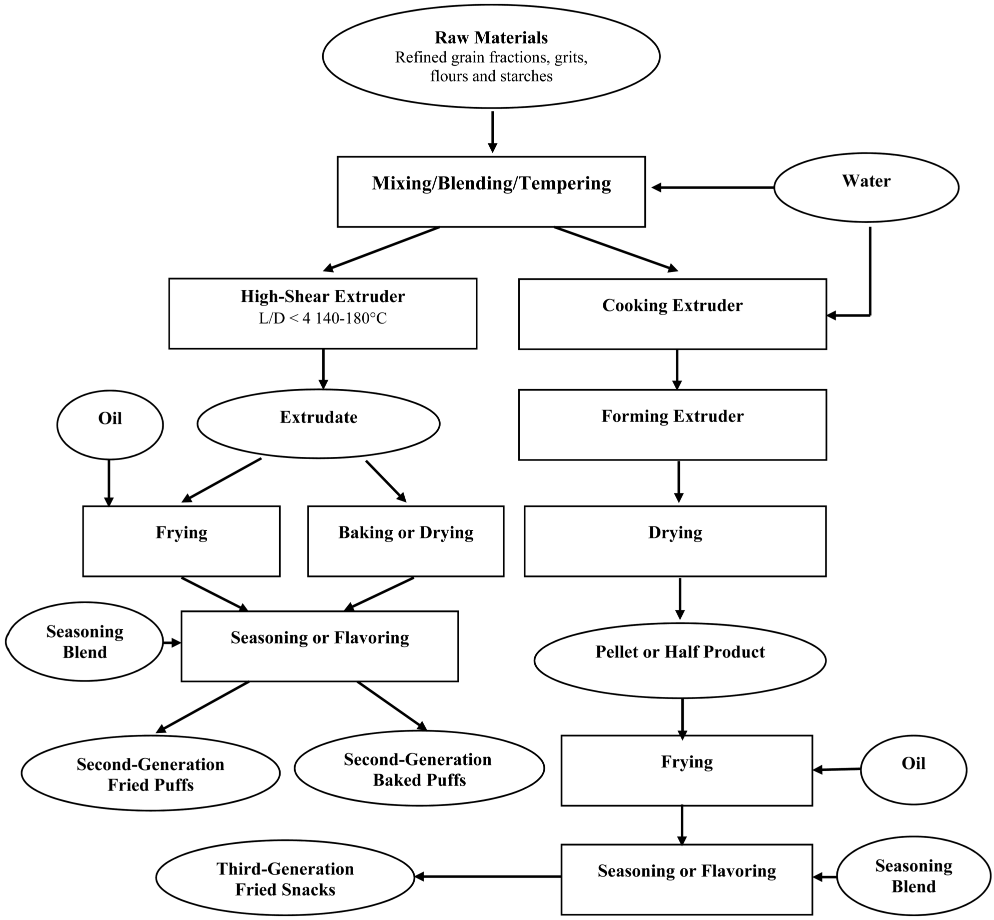


FIGURE 2.2 Flowchart of the manufacturing of directly expanded and third-generation snacks. Adapted from Serna-Saldivar (2010).

The use of non-starch carbohydrates like cellulose, guar gum, pectin, resistant starch, and β-glucans to manufacture directly expanded extruded foods has not been deeply explored. Nevertheless, during the last ten years, several research groups have studied the performance of non-starch polysaccharides on the quality of extruded snacks (Martinez-Bustos et al. 2011, Makowska et al. 2013, Paraman et al. 2015). One of the main reasons to use nonstarchy carbohydrates is to produce healthier foods. However, the search for novel ingredients with innovative characteristics is also studied. Although some ready-to-eat foods, mainly breakfast cereals, are available in the market, only a few examples can be considered low-glycemic index foods due to their high content of digestible starch and fat (Brennan et al. 2008). In this context, the partial substitution of starch-rich ingredients by noncaloric compounds, such as dietary fiber, is an option that may potentially result in healthier and improved products.

2.2.1.2 Current Trends

The demand of consumers for healthier ingredients, such as dietary fiber, has aroused the interest of food producers to develop and improve extruded snacks. Some in vivo studies have shown that the consumption of extruded ready-to-eat snacks with a high content (about 15%) of fiber substituting starch may decrease the plasma glucose level up to 43% (Brennan et al. 2012). However, due to the limited functional properties of the fiber and the undesirable texture that fiber produced in foods, there are some restrictions in its use in extrusion. Nevertheless, it has been suggested that with the control and correct manipulation of the extrusion process variables and the fiber sources, the fiber's functionality may be improved (Mendonça et al. 2000).

2.2.1.2.1 Effect of Process Conditions on the Fiber Fraction of Extruded Snacks

Nowadays, most determinations of the effects of processing conditions on the extruded snacks properties are mainly based on general models (Bisharat et al. 2013). However, due to the high fiber content in the feedstock, the temperature significantly increases because of the high increment of the extrusion torque and the specific energy. The variation of the process conditions has been studied as an alternative to decrease the undesirable effects resulting from the fiber addition in this technology (Jin et al. 1994, Mendonça et al. 2000). In this context, Bisharat et al. (2013) produced corn extrudates enriched with broccoli fiber. They observed that increasing both temperature and the screw speed reduced the viscosity of the melt and increased starch gelatinization, resulting in a porous product. On the other hand, increasing the tempering water showed a reverse effect. Similar observations were reported in a whole-wheat extrudate with a fiber content up to 12.4% (dwb) in the feedstock. In this study, an increment of the volumetric expansion and product porosity was obtained, increasing the temperature and the screw speed and decreasing the tempering moisture (Robin et al. 2012a). They also showed that increasing the barrel temperature, the screw speed, and the tempering moisture decreased the shear viscosity of the melt. The hardness of the extrudate could be modified by the adequate control of the screw speed and the tempering moisture.

The variation and control of the process variables affect the physical and sensorial attributes of the final product, but it has also been documented that may also modify the nutritional content of the extruded snacks. In this context, Stojceska et al. (2008a,b) produced extrudates using wheat flour and corn starch supplemented with brewer's sent grain and with red cabbage (Stojceska et al. 2009) with the aim to increase the dietary fiber content up to 14.5% (wb). Authors explained how the thermal cooking inside the barrel and increment of the tempering moisture (about 15%) significantly augmented the total dietary fiber, phenolic compounds, and antioxidant compounds in the extruded snacks with red cabbage. The same research group developed a gluten-free extrudate with high fiber content from several materials (e.g., potato and corn starch, wheat flour, milk, and soy). They observed that controlling the processing conditions, such as temperature, solids feeding rate, and screw speed, resulted in products with excellent textural properties and also a fiber content 60% higher compared to snacks produced under standard conditions (Stojceska et al. 2010). On the other hand, the extrusion process may modify certain carbohydrates' structures of the food system inducing to different degrees the polymerization of dietary fiber components. In a model system made of lactose, dextrose, and citric acid, about 60% of dietary fiber was obtained in an extruded product from the polymerization of lactose and low-molecular-weight oligosaccharides, which were soluble and nondigestible (Tremaine et al. 2014). These results suggest that controlling the conditions to produce fiber-rich snacks may result in foods with final quality similar to those made with starch-based ingredients.

2.2.1.2.2 Effect of Fiber Source and Composition on Extruded Snacks

Not only do the process conditions influence the physicochemical and functional characteristics of the final product, but also the composition and characteristics of the raw mixtures subjected to extrusion. The properties of the ingredients affect significantly process variables and quality of the finished product especially in terms of texture, structure, expansion, and sensory attributes. In this context, the high content of fiber negatively modifies the melt within the barrel. This effect has been tried to correct using additives such as glycerol monostearate (Mendonça et al. 2000) and dairy proteins (Onwulata et al. 2001), among others.

The inclusion of fibers or gums in formulations of extruded snacks modifies the pasting properties of the ingredients. This is reflected in the matrix forming nature and the water-binding capacity of the polysaccharides, changing the final viscosities of the melt. This inclusion also reduces the caloric content of the extrudates and decreases the digestibility of the starch (Brennan et al. 2008).

The composition of the fiber, which depends on the fiber's source and the process used to obtain them, greatly influences the selection of the extrusion conditions and the final quality of the snacks. Most studies have focused on the effect of the fiber type and composition of the extrudates. Stojceska et al. (2008b) obtained an extruded snack with 14% of fiber from brewer's spent grain with scarce effect on the color, although they also observed a reduction in the snack expansion. Nevertheless, the addition of starch and the adequate control of the processing parameters produced good quality snacks with up to 30% of brewer's spent grains. They also studied the addition of cauliflower (from 5.6 to 11.6%) as a fiber source in corn-, wheat-, and oat-based snacks. Their results showed that increasing the fiber content augmented the cell density and decreased the thickness of the walls and the moisture absorption index (Stojceska et al. 2008a). Likewise, Robin et al. (2011) evaluated the effect of wheat bran in starch extrudates. This research group showed that increasing the wheat bran at low concentrations increased the force of the extruded foam likely due to the fine structures obtained when low contents of wheat bran were supplemented. It should be noted that not all the added fiber ingredients yield acceptable snack products in terms of physical and sensory properties. The addition of fiber-rich legumes, such as common beans (*Phaseolus vulgaris*) in corn starch-based extrudates, although it resulted in a highly nutritious product, showed meager expansion due to the interaction of the fibers with the starch and besides extrudates showed undesirable color (Anton et al. 2009).

In general, fibers rich in soluble fraction yield extrudates with greater expansion than those rich in insoluble fiber. This improvement is mainly due to the low compatibility between insoluble fiber and starch (Robin et al. 2012a,b). The compatibility between fibers and starch may be improved by reducing the particle size of the fiber so that the contact surface with the starch increases. Blake (2006) decreased the particle size of corn fiber from 250 to 50 μm and concluded that this change considerably increase the sectional or radial expansion of extrudates. Other studies in which the solubility of the fiber was chemically modified using an alkaline treatment with NaOH showed an increase in solubility. The enhanced solubility made possible to obtain extrudates with higher expansion rates (Figure 2.3). The alkali modified fiber changes the apparent viscosity of the melt yielding produced higher crumb cells or bubbles in extrudates (Pai et al. 2009). Therefore, the effect of fibers on the texture of extruded snacks mainly depends on the interactions of the starch and the quantity and composition of the used fiber.

The use of insoluble fibers significantly reduces the expansion volume and increases the product density and hardness. The differences in the expansion volume of the fiber-rich extrudates can be explained by the water absorption, the effect of the viscoelastic properties of the melt when it emerges from the die, and the stabilization of the cell wall during the formation of internal or air cells. Some pretreatments, such as reducing the particle size and the increment of the fiber solubility, improve the properties of the final product (Robin et al. 2012b). However, it is not only the increment f soluble fiber that may improve the expansion and texture properties of extruded snacks. In this context, Peressini et al. (2015) elaborated on cereal-based extruded snacks with up to 7% of inulin (a well-known soluble fiber with prebiotic properties). In this research, inulins with two

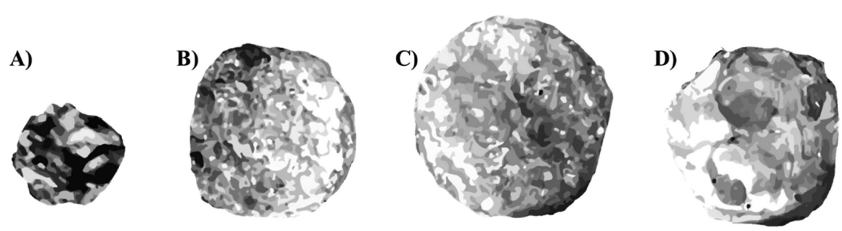


FIGURE 2.3 Extruded snacks with a high dietary fiber content (26%) with different soluble:insoluble dietary fiber weight-ratio. (A) 0.004:1, (B) 0.084:1, (C) 0.193:1, and (D) without fiber. Adapted and modified from Pai et al. (2009).

different degrees of polymerization (10 and 23) were used and compared. They observed that snacks produced with the lower molecular weight inulin showed better expansion and crispness compared to those elaborated with the high-molecular-weight counterpart.

The moisture content of extruded snacks containing fiber sources may modify the hygroscopic properties of the materials and therefore potentially cause textural problems during the shelf life. Tudorica et al. (2002) conducted SEM observations which showed that increasing the soluble fiber content resulted in changes in the hygroscopic properties due to the microstructural modifications. The results mentioned in this section suggest that the proportion of the different fiber fractions (soluble and insoluble) defines the capacity of these non-starch polysaccharides to be used in the manufacture of high-quality extruded snacks.

2.2.1.3 Modification of Snacks' Ingredients Using Extrusion

The technological functionality of the non-starch carbohydrates, such as fibers and gums, used in extrusion processes depends on their composition and the ratio between their soluble and insoluble fractions. Different technologies have been employed to modify these fractions and the fiber structures with the aim to improve functionality. The most utilized technologies are chemical and thermal modifications aimed to promote the partial hydrolysis of cell walls and fiber components and therefore their functional properties (García-Amezquita et al. 2020, Tejada-Ortigoza et al. 2020a). However, other technologies, such as drying (Amid and Mirhosseini 2012), milling (Chau et al. 2004), or even nonthermal processes, such as high hydrostatic pressure (Tejada-Ortigoza et al. 2017) and ultrasound (Martinez-Solano et al. 2020), also affect the composition and functionality of fiber sources. Thermoplastic extrusion effectively modifies non-starch polysaccharides. Several studies have shown that the thermal effect, the tempering moisture, and the shear produced by the screws work together to change these compounds (Larrea et al. 2005).

Studies conducted in cereals have shown that extrusion increases the fiber content and modifies the fiber profile. Østergård et al. (1989) reported that the fiber content in barley increased with extrusion while the starch content decreased with the same treatment due to the formation of nondigestible starch fragments. Similar observations were reported by Vasanthan et al. (2002), who significantly increased the soluble fraction and the type-3 resistant starch contents by transglycosylation.

On the other hand, the use of extrusion to modify the fiber content and composition of non-conventional sources, such as fruit and vegetable by-products, has been explored due to the high soluble fiber content. This alternative could be a solution for the production of high-quality fiber-rich extruded snacks (Table 2.1). Larrea et al. (2005) studied the effect of different extrusion conditions (83–167°C, 22–38% tempering moisture, 126–194 rpm) on the fiber fractions of orange pulp. Their results showed a decrement in the total fiber content accompanied by the increase of the soluble:insoluble fiber fractions ratio, from 0.37:1 to 1.15:1. These results agree with those reported by Mendez-García et al. (2011), who increased the soluble fraction (from 38.6 to 50%), decreasing the insoluble fraction (from 57.01 to 48%) in lemon peel. For their part, García-Amezquita et al. (2019) applied different extrusion processes (70–160°C, 24–58% tempering moisture, 100–200 rpm) to orange peel. They observed that in all treatments, the loss of insoluble fiber correlated to the increase in the soluble fraction, resulting in improved functional properties. The same correlation was reported by Jing and Chi (2013) in soy by-products processed with a twin-screw extruder at 110°C, 30% tempering moisture, and 180 rpm. These results suggest that the extrusion process may partially solubilize the insoluble fiber without the complete degradation of the polymeric structure.

2.2.2 Frying

2.2.2.1 Frying Principles and Fundamentals

Deep-fat frying is considered one of the most universal methods for cooking foods and is still widely used by practically all cultures on the planet. This process is greatly affected by the source,

TABLE 2.1
Substitution of Starch-Based Ingredients Using Fruit or Vegetable Fiber to Produce Extruded Snacks

Extruded Snack Base	Source	Cereal/Starch Substitution (%)	Effect of the Substitution	References
Barley flour	Tomato pomace	2–13	Similar hardness to control snack and higher sensory acceptability.	Altan et al. (2008)
Corn starch	Carrot pomace	5–15	Higher expansion and improved surface.	Kaisangsri et al. (2016)
Corn starch	Apple pomace	22	Density, hardness, and crispness were similar to control.	Paraman et al. (2015)
Rice grits and flour	fruits by-products blend (orange, grape, tomato)	3–7	Acceptable expansion and sensory attributes.	Yağcı and Göğüş (2008)
Wheat flour	Cauliflower	5–20	Higher water absorption index with scarce effect on hardness.	Stojceska et al. (2008a)
Wheat/corn flour	Orange bagasse	3–10	Higher expansion ratio and lower bulk density.	Pitts et al. (2016)

Source: Adapted from García-Amezquita et al. (2018).

type, and condition of the frying oil and processing parameters that are thoroughly discussed in Chapters 3 and 7. Frying consists of placing the food in hot oil during a certain period of time to achieve delectable texture and flavor particularly of fried foods (Banks and Lusas 2001). Several reactions occur in an instantaneous way in the frying oil and in the food being fried (Figure 2.4). When introducing a food into a fryer, oxygen comes in contributing to oxidation reactions; water also comes in, resulting in fat hydrolysis and in the increase in fatty acids, mono and diglycerides, and glycerin. Leachable metals and colored compounds remain in the oil with some lipids from the food. In frying, heat transfer and mass transfer are the transport phenomena leading the process.

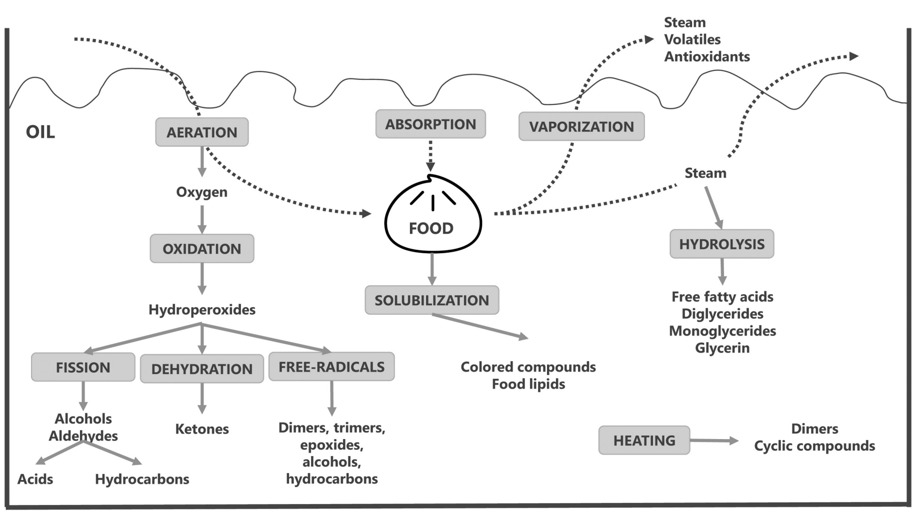


FIGURE 2.4 Reactions and chemical compounds produced during food frying. Adapted from Fritsch (1981).

Microstructure, molecular diffusion, capillary forces, and pressure gradients play an important role during the oil/water mass transfer when dealing with porous foods.

2.2.2.2 Frying Process

The general frying process described by Vitrac et al. (2000) relies strongly on the temperature. First, the initial heating where superficial boiling takes place and where the highest temperature difference between the oil and the product is observed. Then, the following period is related to the vaporization of free or capillary water. Here, free water is still being vaporized but also the boiling of free water moves toward the geometric center of the product. This water will move through the capillaries of the product to achieve the superficial region. Finally, the third stage has low drying rates and is when the product reaches the frying oil temperature that generally fluctuates from 140°C to 190°C. This process is detailed as follows (Banks and Lusas 2001).

2.2.2.2.1 Fryer Entry

Right after its immersion in hot oil, the starch contained in the food's surface is gelatinized and the product is immediately covered in bubbles as superficial boiling starts. The bubbling increases fast and avoids the sticking together of the product pieces. Simultaneously, a temperature front moves to the center by conduction. At this stage, the temperature difference between the oil and the product is the greatest, as well as the external heat flux (Vitrac et al. 2000). Steam evolution helps in limiting the product temperature to water's boiling point, also restricting the penetration of oil to the product.

2.2.2.2.2 Case Hardening

The cells situated on the surface of the product dehydrate and flatten. Only slight changes in the steam evolution can be observed while case hardening happens, and, in parallel, surface bubbling continues in some sites more rapidly than others. The initial moisture in the product is converted to steam, opening rupture channels in the structure of the product as surface moisture diminishes. Up to this point, dehydration has not allowed the formation of a crisp surface although the structure already shows some damage. Unlike other drying processes, during frying there is no true constant drying rate.

2.2.2.2.3 Surface Firming

The following layers of surface cells start a dehydration process, developing a crust structure. If the product is fried at high temperatures, then a thin and light-textured crust is developed; however, if the frying occurs at lower temperatures, the process is slower and results in a thicker crust and crunchier texture. Below the crust layer, the cell structure breaks leading to the formation of a hollow interior structure influenced by the frying temperature. At this point, both the crust and the internal structure are not yet terminated, but the elements affecting the texture in the finished product have been set.

2.2.2.2.4 Cooking/Moisture Reduction

The main objective of this phase is the penetration of heat and the reduction of moisture. It is important to highlight that uniformity in size of the products being fried is crucial for determining the cooking process and the time-temperature profile.

2.2.2.2.5 Finish Frying

During this stage, the temperature on the surface approaches the oil's temperature in a rapid manner. Flavor-producing reactions involving proteins and carbohydrates are produced by the low moisture content and the high temperatures. The increasing temperature in the oil allows a final moisture reduction resulting in a crust with a crispy texture. The oil intake increases during this stage, but it remains mostly on the surface of the product. To assure an optimum quality, the timing to remove the fried product must be precise.

2.2.2.2.6 Oil Absorption

Surface moisture, capillary action, and vacuum absorption are the factors affecting the oil intake by a product during frying. During the first stages, the moisture in the surface governs the absorption, followed by the capillary absorption. A large amount of oil associated with the final product is the one carried out of the fryer on the product's surface. During cooling, while water vapor contained by the product condenses, a partial vacuum effect occurs causing the absorption of oil on the surface of the product.

2.2.2.3 Current Trends in Frying

Recently, frying has experimented with novel solutions and alternatives that fit more the consumer's awareness on the impact of diet on health. The current strategies are focused on the reduction of oil uptake and on the increase in the stability of oil quality (Mellema 2003, Olayemi Oladejo et al. 2017, Pankaj and Keener 2017). The reduction of oil uptake targets the development or the use of alternative technologies for frying such as pressure frying, microwave frying, vacuum frying, radiant frying, or air frying. Besides, preprocessing and postprocessing treatments are suggested to achieve this goal (Figure 2.5).

2.2.2.3.1 Preprocessing Strategies

The use of batter and coatings is one of the strategies to reduce oil uptake since this is a function of the surface area of the material (Mellema 2003). Actually, this strategy has been reported as the most effective way to diminish oil absorption during frying according to Liberty et al. (2019). Commonly, coatings or batters have low moisture content, low moisture permeability, or thermogelling characteristics (Garcia et al. 2004). They also act as a barrier that avoids moisture loss (Liberty et al. 2019). For instance, the addition of hydrocolloids and gums (methylcellulose, carboxy methylcellulose or CMC, carrageenan, hydroxypropyl methylcellulose, pectin, guar gum, xanthan gum, locust bean gum, among others) into formulations helps in the reduction of oil uptake because they serve as a protective layer in the surface of the material (Garcia et al. 2004, Liberty et al. 2019). Recently, the effect of hydrocolloid addition on the batter of deep-fried banana fritters has been studied (Vengu et al. 2020). Hydrocolloids increased the batter pick-up and viscosity of the batter formulation resulting in a reduction of up to 55% oil content and equal sensory acceptance when

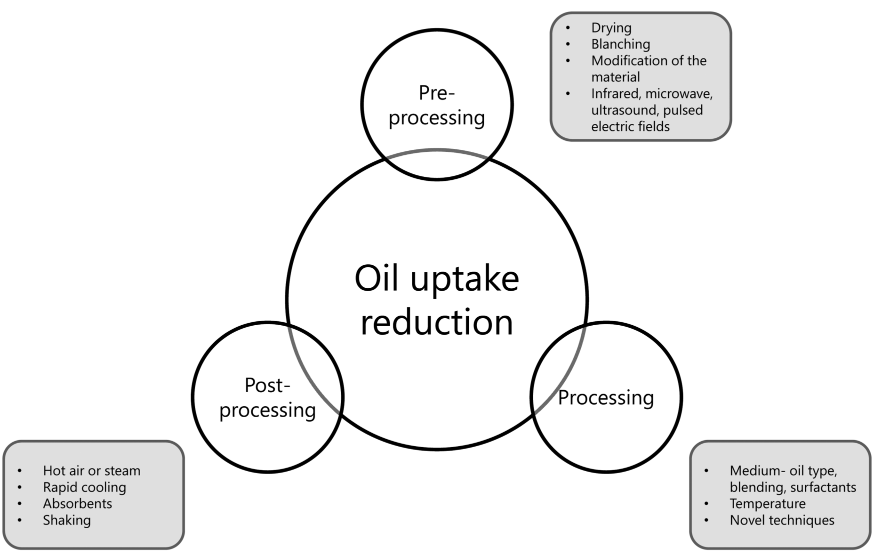


FIGURE 2.5 Strategies to reduce oil uptake during frying processing. Adapted from Pankaj and Keener (2017).

compared to the control. Fiber has also been added to a gluten-starch matrix to improve the quality attributes reducing the oil absorption (Dueik et al. 2014). In this work, the addition of wheat bran to the formulation achieved a reduction of up to 35% of oil uptake, resulting also in a high fiber content product. Wheat flour, a β-glucan source, has also been used in formulations to decrease the oil uptake of wheat chips (Yuksel et al. 2015).

2.2.2.3.1.1 Dehydration Drying is one of the most used strategies to reduce the absorption of oil during frying. The above because, in principle, if the layer at the surface has a low moisture content, less oil is retained. This reduction is also related to the shrinkage and plasticity that the food microstructure develops. In addition, when hot air drying is applied in starchy products, gelatinization might occur on their surface creating a barrier that avoids the penetration of oil (Dehghannya et al. 2016). Predrying has been applied in several products such as potato chips resulting in low-fat content and with the same level of sensory acceptance (Cruz et al. 2018). Ultrasound-assisted air drying has also been applied as pretreatment to potato strips before frying (Dehghannya et al. 2016). A combination of *novel technologies* like ultrasound and microwaves have been applied as pretreatment to improve the frying process. Fan et al. (2019) have evaluated the effect of osmotic-ultrasound dehydration as pretreatment to improve frying of purple-fleshed sweet potato. In addition, these authors applied microwave to assist vacuum frying of the material.

2.2.2.3.2 Processing Strategies

Several strategies have been recently proposed to improve frying processes. One of the most popular ones is air frying, due to the several domestic equipment currently available in the market. Some of the advantages of this technology are the reduction of expenses related to oil consumption, the reduction of the emission of contaminants to the environment, and the most attractive one is the offering of a healthier diet to the consumer (Zaghi et al. 2019). This technology uses small amounts of fat in a closed chamber. During this process, external deposition of oil droplets dispersed through a hot air stream is applied onto the product. Equipment design provides extremely high heat transfer rates between the product and the air in the chamber. In addition, the air is distributed uniformly through the product and thus a significantly lower amount of oil is used (Teruel et al. 2015). A comparative study between deep frying and air frying using different frying oils was performed by Santos et al. (2017). Air-fried potatoes contained about 70% less fat compared to the deep-fried counterparts and the novel technology also reduced the concentration of acrylamide (Chapter 20). Deep-fat frying, electrostatic frying, and vacuum frying were compared to air frying, being the last technology the one that yielded the lowest fat contents (9.8%) in fried fish skins (Fang et al. 2021).

Vacuum frying is a processing alternative for fried products which potentially yields products with high-quality attributes and low acrylamide content (Ravli et al. 2013). The use of vacuum conditions reduces the boiling point of water in the food, resulting in the elimination of moisture at lower temperatures thus frying is performed at lower oil temperatures. Because of these temperatures, nutrient preservation, oil quality protection, and toxic compound generation reduction can be achieved (Dueik et al. 2012). Moreover, the oil uptake in frying occurs during cooling and if vacuum conditions are applied, this cooling stage includes a period of vacuum break. This pressure recovery directly impacts the final oil content in the product. According to Mir-Bel et al. (2009), draining times and vacuum break velocity have a significant influence on oil uptake. Belkova et al. (2018) evaluated the use of vacuum frying achieving the minimization of acrylamide formation and the reduction of other undesirable chemical changes in frying oil that are discussed in Chapter 20.

Infrared radiation is also a promising technology to improve the frying process. Infrared radiation is transmitted as a wave that converts into heat once it gets to the water molecules and ions at the surface of the food. This technology provides less degradation of nutritional compounds when compared to convective or conductive mechanisms. It also has higher thermal efficiency with more uniform heating, impacting positively the energy costs and the processing time (Udomkun et al.

2019). Udomkun et al. (2019) tested how far infrared or conventional heaters affected the distribution of heat and the physicochemical properties of chicken nuggets. A more uniform distribution and a higher heating rate were observed with far infrared frying. No significant differences were observed in the physicochemical properties of the product. Additionally, infrared radiation saved energy and prolonged the shelf life of the frying oil.

Novel treatments have also been used in combination with vacuum frying to improve the process. The effect of ultrasound using microwave-assisted vacuum frying has been studied on the frying rate and quality of mushroom chips (Devi et al. 2018). These authors concluded that the combined technologies accelerated frying rate, diminished oil uptake, and produced mushroom chips with better texture and color when compared to vacuum-fried samples. Likewise, Sun et al. (2019) investigated the impact of this combination of processes on the frying oil quality and concluded that the assisted technologies delayed the deterioration of the frying oil. Sun et al. (2018 a,b) have also used the combination of these techniques to potato chips and concluded that the assisted methods decreased oil uptake and improved the texture and color properties of finished products. Additionally, these authors observed a decrease in energy consumption.

2.2.2.4 Postprocessing Strategies

The major portion of oil absorbed during frying occurs when the product is removed from the fryer and starts the cooling stage (Hoon 2010). Because of this, some strategies have also been proposed such as de-oiling the final product during the cooling period. De-oiling using a centrifuge helps in the removal of the surface oil resulting in a reduced oil content of the final product. Centrifugal forces facilitate the separation of the oil from the porous surface (Hoon 2010). These de-oiling mechanisms are commonly combined with other strategies to improve the frying process and the final product characteristics. Sothornvit (2011) proposed post-frying centrifugation of vacuum-fried banana chips. The combination of an edible coating and a high centrifugation speed leads to a reduction in the oil absorption of up to 33.7%. Moreira et al. (2009) explored the effect of centrifuging as a de-oiling mechanism of vacuum-fried potato chips. After centrifugation, the samples had a reduction of oil content of 77% when compared with the noncentrifuged ones. Post-frying vacuum applications have been applied by (Ahmad Tarmizi et al. 2013). Under vacuum conditions, draining of the final product reduces its moisture content. When compared to atmospheric drainage, vacuum drainage briefly diminished both the oxidization of the product and the generation of free fatty acids by 50%. Similarly, Ravli et al. (2013) studied a two-stage frying process (vacuum frying coupled to a de-oiling mechanism) to produce low-fat sweet potato chips. Their process reduced about 15% of the oil content when compared to their single-stage (only vacuum frying) process. More strategies during this critical stage are needed in order to reduce the oil content of the product without affecting the physicochemical and sensorial properties of the final snacks.

2.2.3 Drying Principles and Fundamentals

Drying is one of the oldest and most common unit operations applied to snacks. During drying, the water is eliminated to achieve a target content, resulting in a longer shelf life due to less water available for microorganisms and undesirable reactions. Because of this, it is a process commonly used in the production of many vegetable and animal-based snacks. The dehydration process is widely employed for the production of natural fruit rings or veggie chips and dehydrated animal/marine products discussed in Chapters 16 and 18. This unit operation involves heat and mass transfer that affect important chemical and physical transformations in the food matrix that undoubtedly affect end-product quality. Shrinkage, puffing, glass transitions, nutrient reduction, changes in color, odor, texture, are some of the changes that can occur during this process (Mujumdar and Devahastin 2004, Ibarz and Barbosa-Cánovas 2005).

The mechanisms of water transfer that occur during drying are: the water movement under capillary forces, diffusion due to concentration gradients, superficial diffusion, vapor diffusion in the

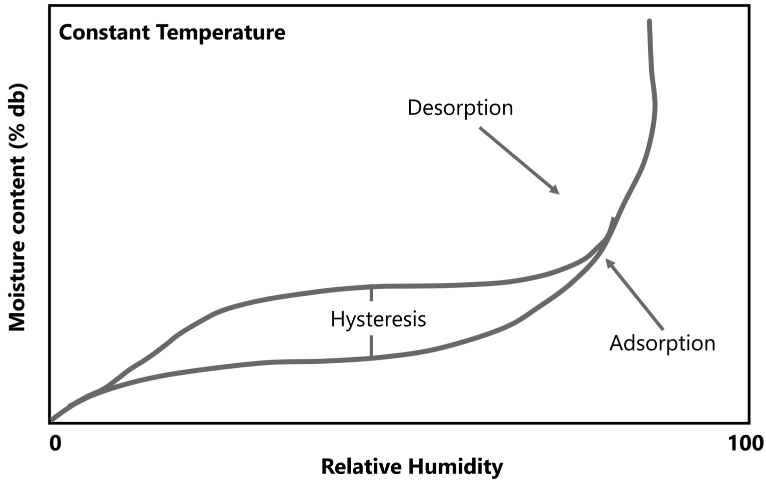


FIGURE 2.6 Typical adsorption and desorption isotherms.

pores filled with air, flow due to hydrostatic pressure gradients, and the combination of these phenomena. The material to be dried is also an important factor because of the possible changes that occur while eliminating the water contained in the food matrix (Ibarz and Barbosa-Cánovas 2005).

2.2.3.1 Drying Process

The equilibrium moisture content (EMC) is the moisture of a solid in equilibrium with air at a given relative humidity (or water activity, a_w) at a specific or fixed temperature. A sorption isotherm is the EMC (g water/100 g solids) of a product plotted against the relative humidity or a_w at a determined temperature (Chirife and Iglesias 1978, Al-Muhtaseb et al. 2002, Basu et al. 2006, Peleg 2020). Figure 2.6 shows typical adsorption and desorption isotherms, and their difference (hysteresis). The knowledge of this behavior, mainly the desorption one, is crucial when setting processing conditions for drying and selecting storage and packaging conditions of snack products.

Water sorption data is determined experimentally because, besides the temperature, the physical structure and the materials' composition and interactions affect the water sorption process. Physical and/ or chemical modifications such as the pore structure and size can cause important variations in the moisture-binding capacity of the material (Mujumdar and Devahastin 2004). Recently, a way to predict moisture sorption curves from three experimental data (initial moisture content and two more at different times) was proposed by means of a mathematical method by Tejada-Ortigoza et al. (2020b). During the drying process, *kinetics* is crucial to determine and predict the behavior of the material. Generally, once the material passes through an initial period of adjustment, the moisture content decreases linearly with time due to the evaporation of water. Then is followed by a nonlinear decrease in moisture content until the solid reaches an EMC.

Finally, another important term in drying processing is A_w, which is the availability of water for microorganisms' growth and for chemical reactions. It is defined as the ratio of the partial pressure and the equilibrium vapor pressure of water at the same temperature. Also, the amount of water and temperature defines the region in a state diagram at which a snack is, depending on its desired sensorial characteristics. Physical changes related to glass transition are a function of the moisture content. This will also have an impact on the stability and the shelf life of the product (Labuza and Hyman 1998, Payne and Labuza 2005). In low-moisture snacks, the loss of crispness due to water plasticization is an undesired phenomenon caused by the glass transition (Roos et al. 1998). The importance of this concept in snacks relies on its effect on crispness or gumminess as a textural characteristic, which is a major cause of product rejection by consumers (Katz and Labuza 1981). For instance, moisture content has an effect on the texture of most dry snacks by means of softening or plasticizing the matrix, altering the mechanical properties of the snack. Because of this, it has been suggested that textural acceptance in the snack industry can be defined as a function of A_w. For popcorn (Chapter 9), saltines (Chapter 10), puffed corn curls (Chapter 12), and potato chips (Chapter 14), the sensorial acceptability found ranged between A_w values of 0.35–0.50, where amorphous to crystalline transformations occur (Katz and Labuza 1981). Besides, it must be considered that at this A_w range lipid oxidation might also occur. Water might have a protective effect against oxidation at certain A_w (Labuza et al. 1972).

2.2.3.1.1 Equipment

The basic and general configuration of a dryer is a chamber where the food is introduced, equipped with a ventilator, and conducts that allow the circulation of the hot air through and around the product. Water is eliminated from the surface's product and conducted outside the dryer through an air flow. Several classifications of dryers have been proposed according to their mode of operation such as heat input, operating pressure, drying medium, drying temperature, and stages. Figure 2.7 depicts the most common drying systems.

Dryers are also classified based on their mode of thermal energy input into direct or convective and indirect dryers. Direct dryers are the most common ones in the industry despite their comparatively lower thermal efficiency. Indirect dryers are the ones that transfer the heat to dehydrate the material using a medium like steam, gas, or thermal fluids. These dryers commonly use vacuum or a gas flow to remove the moisture from the chamber.

2.2.3.2 Current Trends in Drying

The research in this area is focused on finding solutions to reduce the negative effects of the process, i.e., changes in cellular and chemical structures that led to physical variations and oxidative reactions. In addition, research is also aimed to study the addition of compounds with protective effects during the process, the development of structural elements for encapsulation before spray drying, and the promotion of reactions that result in positive functional changes (Betoret et al. 2015). Many of these studies converge in the development of healthy snacks based on fruits and vegetables (Chapter 16) due to their vitamin, minerals, and bioactive compounds with a positive impact on the human diet (Chen et al. 2018, Donno et al. 2019, Nowacka et al. 2019).

The use of freeze-drying is one of the most common methods to produce fruit and vegetable snacks and the development of healthy bars because, contrarily to the conventional hot air drying, yields crispy products with desirable color and texture (Chen et al. 2018, Ciurzyńska et al.

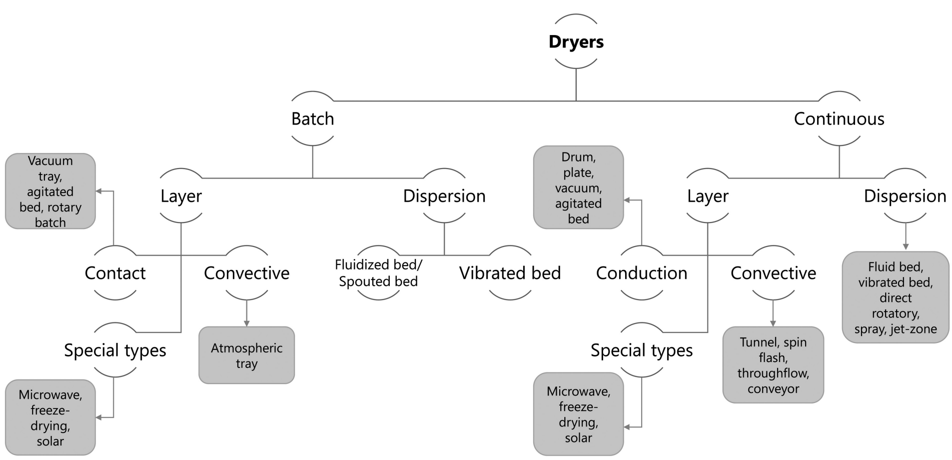


FIGURE 2.7 Drying systems applied to the production of snacks. Adapted from Baker (1997) and Mujumdar (2004).

2020). Apple, goji, kiwi, and kaki were freeze-dried to be consumed as snacks and the main health-promoting phytochemicals determined with the aim to stimulate large-scale exploitation of fruits (Donno et al. 2019). Likewise, probiotic enriched apple snacks have been dried by freeze-drying followed by microwave-vacuum drying (Li et al. 2018).

Freeze-dried vegetable snacks using hydrocolloids were developed by Ciurzyńska et al. (2020). Sodium alginate with calcium lactate and locust bean gum with xanthan gum was used to create a porous structure in the vegetable bar. The authors concluded that although a high-quality final product was obtained, freeze-drying is an energy-consuming process with high capital costs.

2.2.3.2.1 Microwave Drying

Microwave drying is not a common process applied in mass production in the food industry, although it has been studied as an alternative to hot air drying because it requires shorter drying times and lower temperatures (Hnin et al. 2019, Ciurzyńska et al. 2020). The development of equipment with combined methods to improve the quality of the final product is constantly studied. Microwave-vacuum drying is a variant of this method and it has been coupled with a freeze-drying system to shorten the processing time with results similar to the ones obtained in freeze-drying but with a reduction in the energy consumption due to shorter drying times (Hnin et al. 2019). These combined methods have been researched by Hnin et al. (2019) in the development of rose powder-yam snack chips resulting in high scores of sensory attributes and higher retention of total phenolics and anthocyanin pigments when compared to hot air or single microwave-vacuum drying. Similarly, combined freeze-drying and microwave-vacuum drying has been used to yield functional okra snacks with the advantages of significantly reducing the drying time and the energy consumption when compared to conventional hot air drying (Jiang et al. 2017). The effect of microwave-vacuum drying has also been compared to osmotic dehydration for the production of dried cranberries. Ultrasound and pulsed electric fields were used as pretreatments to improve the drying process (Nowacka et al. 2019).

2.2.3.2.2 Infrared Drying

Drying with *infrared* rays is a highly efficient method because energy is transferred directly to the product surface without heating the surrounding air (Chen et al. 2018). Consequently, it is an energy-saving method with a shorter processing time compared to convective drying. However, the infrared emitter might represent a comparatively higher investment cost (Ciurzyńska et al. 2020). Infrared has been successfully used as pretreatment to improve the conventional drying methods. Chen et al. (2018) evaluated the use of sequential infrared blanching and hot air drying to develop a crispy carrot snack resulting in a reduction of drying times (32, 41, and 45%) when applying 60°C, 70°C, and 80°C. The infrared pretreatment also led to crispier and more colorful products when compared to the noninfrared-treated samples.

2.2.3.2.3 Explosion Puffing Drying

This is an alternative to produce snacks with similar structural characteristics to those obtained by freeze-drying. It is an intermediate stage in the drying process caused by either a sudden increase in temperature or a sudden decrease in pressure that causes the water in the product to vaporize. The sudden water vaporization results in an expansion and creation of an internal porous crumb structure with less time and energy expended (Zou et al. 2013). Instant controlled pressure drop has also been used to produce crispy materials with a similar approach to puffing drying. Recently, Peng et al. (2018) evaluated the application of this method to fabricate dried carrot chips.

2.2.4 Baking

Various sorts of chips, crackers, pretzels, extruded snacks, and legume and tree nuts are produced by the application of heat in an oven (baking). The use of this thermal operation plays relevant roles in today's diet and consumers' interest due to the calories intake. Compared to frying, baking is an option to provide low-fat or fat-free snack foods (Oluwole et al. 2014). For the snack industry, baking enhances the reduction of moisture with the aim of getting desired organoleptic properties and longer shelf life. As in drying, concepts such as initial and final moisture contents, A_w, and water evaporation rate during the process are crucial to understanding the process. For instance, crispness and other mechanical parameters are closely related to A_w and glass transition (Oluwole et al. 2014, Roos et al. 1998). However, baked snacks not only look for the reduction of the water content of the product but also in the improvement of relevant sensorial features such as texture and flavor.

The concepts of "crispy" and "crunchy" are part of a complex of sensations that includes flavor, taste, odor, sight, texture, and sound. These firmness and brittleness are specially important because they affect how the snack fractures and disintegrates while being masticated (Dijksterhuis et al. 2007). The baking process is performed during a specific period of time and a particular temperature depending on the desired final characteristics. Temperature is one of the main parameters to consider because it controls Maillard reaction that leads to desirable sensorial qualities such as color, taste, and crispness (Nath and Chattopadhyay 2007, Oluwole et al. 2014). Because of this, baking is considered one of the most sensitive processes because it influences the chemical, physical, and sensory qualities of snacks and also affects production cost (Khatir et al. 2015).

Heat transfer during baking generally occurs in three major possible means: convection, conduction, and radiation. Besides the heating temperature and the time, the velocity of the heating medium and the nature of the food product are other factors affecting the final quality of the product. Thus, optimization of the oven parameters is crucial to assure temperature uniformity, efficiency, and humidity level inside the oven. The conduction mechanism governs during baking of snacks at low temperatures. Then, when the temperature is increased, simultaneous heat and mass transfer occur, where the evaporation-condensation mechanism dominates (Purlis and Salvadori 2009, Chhanwal et al. 2011, 2019). Here, water evaporates and vapor condenses at the colder side of the gas cells until the inside of the product reaches a temperature of 100°C (Chhanwal et al. 2011). The way the heat is provided plays an important role in the crust formation, browning, and flavor development of the baked snack. The industry constantly looks for ovens where the process can be accelerated, the yield increased, and the cost reduced while keeping or enhancing product quality (Chhanwal et al. 2019).

2.2.4.1 Current Perspectives on Ovens for Baking

Innovation and improvements in baking technology are mainly focused on final product quality, nutritional composition, and economic considerations (Mondal and Datta 2008). For small-scale production, electric ovens are commonly used; however, for large-scale operations, a light diesel oil-operated oven with digital temperature indicator and timer is normally used (Nath and Chattopadhyay 2007). These common convection ovens have the advantages of yielding good quality products and are relatively easy to design even though they are not as efficient and require longer baking times. Currently, hybrid heating techniques have proved to enhance the energy efficiency of the process maintaining the quality of the product. Besides convection, ovens using technologies like microwave, infrared, jet impingement have been recently studied (Chhanwal et al. 2019).

2.2.4.1.1 Microwave Oven

As previously reviewed, microwave technology has been widely used both in household and food industries not only for drying and baking, but also for thawing, heating, and cooking because this technology allows drying and precise control. It has the main advantages of eliminating pre-heating steps, instant start-up, space-saving, accuracy, and energy efficiency. However, quality parameters such as browning, starch gelatinization, and volume expansion ideal for snacks are affected by this technology. Along with these, nonuniform heating, increased cold and hot spots, and gummy texture are some other difficulties when baking using microwaves (Rakesh et al. 2009).

Microwave ovens generate the heat from inside the food, and then the heat is transferred by convection to the rest of the product. These patterns affect product characteristics. Moreover, due to the fast generation of heat, there is not sufficient time for gelatinization, expansion, and flavor development (Chhanwal et al. 2019). However, the combination of methods might be an option to improve the results obtained with this technology.

2.2.4.1.2 Infrared Oven

Infrared radiation is widely used because of its rapid surface heating capacity. The electromagnetic radiation has a wavelength ranging from 0.78 to 1,000 μm, being the far-infrared the most suitable for heating foods. Besides its enhanced efficiency, it also presents many advantages like reducing processing times, energy expenditure, uniform surface heating, and good sensorial and nutritional value of cooked foods. Some disadvantages of this technology are low penetration power inside the product and that heating is influenced by the characteristics of the snack surface and penetration depth of the radiation. For this technology, the penetration depth depends on the moisture content and it is affected by the wavelength. For this reason, the penetration depth varies significantly among food materials (Chhanwal et al. 2019, De Pilli and Alessandrino 2020).

Even though, infrared baking has been extensively studied for breads, cakes, or cookies but not for savory snack production. In general, in these studies, researchers have reported poor quality of the final products. For snacks, radiation has been mainly used as a roasting method for nuts (Chapter 13) because enhances flavor, color, texture, and appearance (Bagheri et al. 2019). Roasting nuts by infrared radiation has been extensively revised by Bagheri (2020).

2.2.4.1.3 Jet Impingement Oven

Jet impinging is a process where a jet of fluid impacts the surface of the product to achieve a fast heat and mass transfer. It is a forced convection heating through hot air applied at 10–100 m/s. Jet impingement has been used by many industries (textile, glass, metal, food) mainly for cooling. Nowadays, the food industry uses this technology for cooking, toasting, roasting, and baking with advantages such as high efficiency, short processing times, rapid moisture removal, uniform heating, reduced moisture loss, and most importantly, quality parameters like the ones obtained after usage of conventional ovens. This technology allows the reduction of about 25°C of the air temperature compared to conventional ovens which translates into 30% more efficiency. However, it might present disadvantages such as thick crust formation, low porosity, and darker colorations, besides that more energy is required (Supmoon and Noomhorm 2013, Chhanwal et al. 2019). Hot air impingement has been combined with infrared radiation to improve the quality of potato chips (Supmoon and Noomhorm 2013) and the preferred technology to process flash-fried savory snacks with reduced oil and caloric contents. Healthier snacks like apple and jujube slices have been also processed by using this technology as pulsed air (Wei et al. 2018), as a combination with microwave vacuum (Yin et al. 2019), or as hot-air assisted radiofrequency (Peng et al. 2019) with improved final product quality.

2.2.5 Specialized Processes: Principles and Equipment

2.2.5.1 Peelers and Slicers

One of the first stages in the production of snacks based on fruits and vegetables is the removal of skin or peel, as well as cutting the material to obtain the desired size and shape to subject the product to subsequent processes such as frying or drying. Advances in skinning and slicing equipment have been linked primarily to the potato-based industry (Chapter 14). The demand for potato (or other vegetables used in the snack industry) peeler and slicer equipment in many well-established markets is mainly driven by the need for replacements. Hence, most of the demand is to substitute old peeler and slicer equipment with new energy-efficient ones. The top three emerging market trends driving the global potato peeler and slicer equipment market according to Technavio food and beverage research analysts are: increasing focus on energy-efficient equipment, growing preference for automated peeler and slicer equipment, and applied new technological advancements (Technavio 2021).

Designers have introduced eco-friendly potato peelers and slicers, which optimize the efficiency of the production cycle in order to offer better alternatives to mitigate the negative effects of global warming and high energy consumption. This will encourage the adoption of new equipment and drive upgrades. Manufacturers are providing state-of-the-art components such as energy-efficient and electrically commutated motors that are used to exceed energy standards without forgoing performance and capability. The company provides stainless steel commercial peelers equipped with an auxiliary contact for an external electric valve that besides are energy efficient owing to engine optimization.

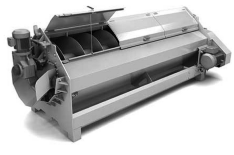
On the other hand, the market is witnessing an increasing demand for automated appliances, owing to their advantages such as lesser risk, efficiency, and quick return on investments. Many units of automated peelers and slicers come with improved features such as laser sorters and automatic defect removal (ADR) systems.

The quick adoption of technology and increasing consumer preference for innovative potato peelers and slicers provide high-quality potato peeling equipment with minimal skin loss, the design uses a combination of peeling and polishing mechanisms to provide a turnkey solution based on the specifications provided by end users. Other options are the water slicing methods, which are designed to apply high pressure to optimize cuts with a lower percentage of waste. All these advancements will likely increase the demand for new vegetable peeler and slicer equipment.

Some examples of industrial equipment used for the removal of skins and peels of fruits and vegetables are depicted in Figure 2.8. The brusher is a machine to remove skin and peel from food, gently remove loose peel, or aggressively product defects by using automatic brushing technology, dry peeler uses a specially designed stainless-steel drum with smooth perforated panels that adapt to each product. Inside the drum, there is an agitator that ensures the continuous mixing of the potatoes or the product to be treated, and the transfer of the remains of skin to the drum, which rotates at high speed using an external shaft so that the peel can thus pass to the pump of dry waste. The dry peeler manages to separate external residues (rest of skin, peel) without using water and with minimal losses of performance. On the other hand, the steam peeler achieves uniformity in the removal of the skin and has managed to reduce the peeling speed and energy consumption by up to 25%.

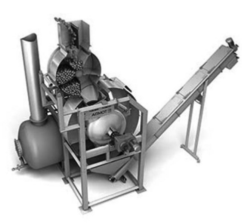
2.2.5.2 Poppers

A large category of starchy snacks is produced via indirect expansion, which happens if snack pellets are deep-fat fried or expanded with hot air or in a microwave oven (Moraru and Kokini 2003). Snacks like popcorn, popped and puffed rice, popped sorghum, popped and roasted wheat,



A) Brusher

B) Dry peeler separator



C) Steam peeler

FIGURE 2.8 Industrial equipment for the removal of skins and peels of fruits and vegetables (https://www.tomra.com/es-es) and puffed soybean and other related legume seeds are examples of products obtained with these technologies.

One of the most popular and widely consumed snacks is popcorn thoroughly described in Chapter 9. Popped corn is made from a special type of maize which considerably differs in terms of physical characteristics and composition from other types used for human or animal nutrition. There are several varieties of popcorn, including rice popcorn, pearl popcorn, red, black, rainbow, yellow, white, and blue. These are known as gourmet specialty popcorn varieties. At present, work is being done to develop new varieties and hybrids with improved quality especially in terms of pop ability and stability of expanded products.

Popcorn kernels are normally environmentally dried to reach moisture levels between 13 and 14%. At this moisture level the popcorn kernels show a higher expansion rate (Metzger et al. 1989). When the popcorn temperature exceeds 100°C, its water content boils and reaches a thermodynamic equilibrium at the vapor pressure, as in a pressure cooker (Hoseney et al. 1983). Above a critical vapor pressure, the hull suddenly breaks. At the same time in the popcorn endosperm, the starch granules expand adiabatically and form a spongy flake of various shapes (Quinn et al. 2005). As shown in the Figure 2.1 the critical temperature (minimum to obtain a high percentage of popped corn) is around 180°C (Virot and Ponomarenko 2015) (Figure 2.9).

There are essentially two sorts of popcorn configurations: mushroom or butterfly. Popped kernels with a spherical shape are called a mushroom or ball type. Due to its configuration, it is preferred in the confection industry because it is less susceptible to breakage, more resistant to handling, and more efficiently coated with flavorings and confectionery syrups. The more popular butterfly type has a higher expansion or lower apparent bulk density, and better mouthfeel and it is preferred for on-premises popping, where it is sold by volume. For the production of mushroom or ball popcorn, more heat should be applied during popping. Temperatures of 215°C and 235°C are recommended to favor the production of butterfly- and mushroom-shaped flakes, respectively (Snack Food Association 1992, Serna-Saldivar 2008).

There are two main methods to popping popcorn: dry and wet methods. The dry method uses dry heat to pop the kernels, such as a fire or an air popper. The more popular and employed wet method uses oil to help distribute the heat and results in a more even popping. Microwave popcorn and most other commercial products are obtained using the wet method. Kernels with the right moisture content will be fluffy and light whereas counterparts with higher moisture will be more dense and gummy. Unpopped kernels have most likely dried out or were mechanically damaged especially in the outer cover or pericarp. On average, a grain pops when it reaches a temperature of 175–190°C (Virot and Ponomarenko 2015). The detailed dry and wet popping processes are deeply covered in Chapter 9.

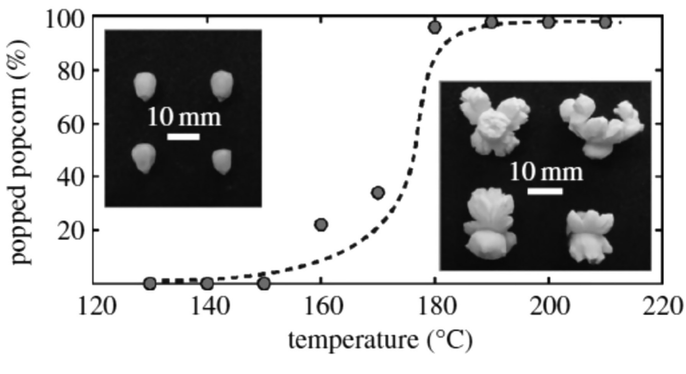


FIGURE 2.9 Percentages of popped popcorn in an oven at increasing temperature; the dashed line is a guide to the eyes. The critical temperature is approximately 180°C (insets). Snapshots of unpopped corn (kernels, left) and popped popcorn (flakes, right) (Virot and Ponomarenko 2015).

2.2.5.2.1 Wet Poppers

Normally, popcorn, oil, and salt are placed into a heated pan for the production of wet popped products. An agitator on the bottom constantly stirs the mixture, allowing better and even heat distribution among the kernels. When the temperature of the popcorn is high enough, the kernels gradually burst. At the moment of expansion, the oil is absorbed, and the salt sticks to the flakes. Poppers are either heated by gas or electricity, the first being the most preferred in the industry. The most frequent popcorn-to-oil ratio is 3:1 (w/w). The popping cycle varies from 2.5 to 3 min. In commercial operations, the wet poppers are usually arranged in tandem with 4 to 8 machines, which dump the popped corn onto a belt conveyor which transports the popcorn to a sifter, which removes unpopped kernels and other fines. After sifting, the popcorn should be immediately packaged to avoid moisture absorption and loss of texture (Snack Food Association 1992, Serna-Saldivar 2008, Serna-Saldivar 2010).

2.2.5.2.2 Dry Poppers

Dry poppers come in two basic types: the older rotary wire drum and the modern steel auger (Chapter 9). The rotary type heats popcorn kernels over an open flame, whereas in the steel auger kernels are thermally treated while traveling along the screw. The heated air is injected with enough pressure to force its way through the kernels, enhancing the transfer of heat. This action also stirs kernels in a fluidized bed fashion (Snack Food Association 1992, Serna-Saldivar 2010). The fluidized bed process has four basic variables: feed rate, temperature (210–230°C), popping time (affected by the rpm of the screw), and heated air pressure. The normal residence times vary from 65 to 105 s. Dry poppers are designed for large-scale operations and can pop up to 70–450 kg/h. When popcorn is processed, it loses 12–13% moisture and 8–10% in scrap (Serna-Saldivar 2008). Dry poppers are usually accompanied by a sifter and a coater or tumbler. The popper should have exhaust ventilation to remove the water vapor generated during processing. The sifting operation should efficiently remove unpopped kernels and broken flakes. The clean popped flakes are then flavored in a tumbler. Oil, salt, and flavorings are directly applied or sprayed onto the product. The main advantage of dry poppers is the possibility of manufacturing reduced or even fat-free popped corn snacks. The final oil content of snacks is controlled during the seasoning operation.

2.2.5.2.3 Microwave Popping

Microwave popping is today considered as a vast and substitute technology for popping grains such as maize, rice, and sorghum. Basically, microwave processing is being performed by electromagnetic radiations with a microwave frequency of approximately 2,450 megahertz (MHz) and the main principle behind food heating is dielectric heating. Besides processing conditions, the moisture content of the incoming food material is highly associated with expansion rate. This is the only food processing operation which transfers the energy from inside to outside of the food products (Solanki et al. 2018).

Microwave popping has also been applied for the expansion of extruded half products or pellets for the production of snacks with lower amounts of calories. The important steps in the microwave expansion of starchy pellets are: (i) the drying before the start of the expansion process, (ii) the start of the expansion process via nucleation, (iii) the actual expansion process due to the growth of individual steam bubbles, (iv) the end of the expansion process via cell opening, (v) the possible (partial) rupture of the cell, (vi) shrinkage of the pellet due to additional drying especially when the pellet is still in the rubbery state, and (vii) the fixation of the expanded structure if the expanded pellet goes into the glassy state. At the end of the heating process the expanded pellets can be (i) burnt, (ii) expanded, (iii) not expanded, or (iv) expanded, but clumped (van der Sman and Bows 2017). For this reason, the microwave process parameters should be carefully controlled especially in terms of power level, power density, and residence time (Sharma et al. 2014). The other critical factor is the design of the pillow-style microwave bag which normally has a susceptor plate that concentrates microwave heat onto the bed of the popcorn kernels blended with oil and flavorings (Chapter 4).

For microwave popping, the recommended power output in conventional microwaves is 660 W for 2 min on high power (Serna-Saldívar 2008).

2.2.5.3 Coating, Flavoring, and Battering

Oil, powder, and granule applicators, including oil and cheese sprayers, powder dispensers, electrostatic salters, and coating tumblers are normally used for snack flavoring, The detailed description of the equipment and flavoring technologies are discussed in Chapter 3.

The snack industry typically employs batch or continuous coaters. Batch coating for salty products is typically performed with an inclined enrobing pan that turns on an axis inclined at 30°. The base product is placed in the pan, and the oil coating and seasonings are introduced as the drum rotates. The coating is either poured as solid blends or pumped with an oil-based flavoring mix. The batch pan is allowed to work until the coating is fully spread and evenly distributed onto the product. The most common way to apply coatings is with a continuous machine consisting basically of a horizontal stainless-steel cylinder that rotates on its axis. The speed of rotation and the angle of the cylinder are adjusted to control the product flow rate or residence time. The coater is equipped with either a dry applicator or a pump system that sprays the coating in the first part of the inclined drum. The disadvantage of the dry powder is that it frequently comes off on the consumer's hands. The most common method is to spray cheese slurry onto the snacks. The cheese flavoring is produced by mixing oil with powdered cheese and other ingredients (Chapter 8). In order to apply the coating, the mixture should be heated to around 50°C to melt the cheese and prevent plugging the spray system. For instance, cheese-flavored popcorn normally contains 15% cheese, 28% oil, and 57% popcorn (Snack Food Association 1992, Serna-Saldívar 2008, Serna-Saldivar 2010).

A special type of coater is used to produce sugar-coated popcorn. The batch system consists of a copper or stainless-steel kettle in which sugar, glucose, and water solution are boiled to make caramel. The boiling solution is then gradually poured into a blender that is made of a rotating drum and a rotating auger inside at one edge. The resulting action lifts and mixes the popcorn with the sugar coating. A small amount of sodium bicarbonate can be added to the syrup to make it foam and double its volume. After the foamed sugar and popcorn are well coated, a small amount of oil/lecithin is sprayed to enhance the separation of the popcorn (Snack Food Association Association 1992, Serna-Saldivar 2008).

For caramel corn, coatings are generally composed of sugar syrup, vegetable oil, and other additives (coloring/flavoring compounds) that are heated at 144–149°C to produce a free-flowing solution (Serna-Saldivar 2008, Serna-Saldivar 2010).

2.2.5.4 Additional Processes

There are additional processes and equipment that are important for the operation of snack production lines, such as the following.

2.2.5.4.1 Transfer and Storage Equipment

In particular, storage of raw materials is of high importance, given that raw materials are natural products that have limited life and can be seriously affected by storage conditions. For instance, the sugar content of potatoes may be higher than desired when potatoes are stored at low temperature (2–4°C) due to lowing of sugars breakdown to carbon dioxide and water (Chapter 14). The sugar content can be lowered back to an acceptable level (< 0.2–0.4%) by reconditioning at > 13°C for several weeks prior to use. The right sugar content in potatoes ensures that Maillard (browning) reactions that result in undesirable dark spots on fried potato chips are avoided.

2.2.5.4.2 Packaging

A primary concern for packaging is to ensure a long shelf life of the finished product (Chapter 4). From a process control viewpoint, ensuring that the weight of packaged snacks is as close to but certainly above the value specified on the package has obvious economic implications.

2.3 APPLICATION OF EMERGING TECHNOLOGIES TO IMPROVE SNACK PRODUCTION

A lot of effort is put to decrease the energy consumption of drying, frying, or other thermal processes applied in the snack industry. This effect might be achieved by shifting traditional technologies like hot-air to microwave-vacuum, high hydrostatic pressure (HHP), pulsed electric fields (PEF), or ultrasound (US). These emerging technologies modify different cellular tissues and food structures that influence the process efficiency and quality of snacks. Dziki (2020) recently reviewed various pretreatments before the application of freeze-drying and concluded that mainly PEF and US presented advantages in terms of accelerating the drying process, generating products with improved sensory qualities and the retention of physical properties and relevant bioactive compounds in final products. Table 2.2 shows specific examples for freeze-dried snacks obtained from fruits and vegetables, confirming the beneficial effect of different pretreatments (HHP, PEF, and US) in terms of reduction of process times and improvement of both sensory and functional qualities. In the case of snacks and other fried foods, a review of Zhang et al. (2020) summarizes the analysis of novel alternative frying technologies, such as microwave-assisted vacuum frying (MVF), pulse-spouted microwave vacuum frying and power ultrasound, and microwave-assisted vacuum frying. Ultrasound microwave-assisted vacuum frying (USMVF) has proven to be efficient to produce products with lower oil content and better texture characteristics. In addition, different pretreatment technologies, such as HHP, PEF, US, and infrared radiation employed as post-frying processing, can be applied with positive synergistic effects. The operation and application of HHP, PEF, and US as pretreatment in the production of snacks are reviewed below.

2.3.1 High Hydrostatic Pressure (HPP) as Pretreatment in Snacks Elaboration

HPP is a nonthermal technology that has been adopted by various segments of the food industry in the past 30 years. The potential of maintaining nutritional, sensory, and quality while inactivating pathogenic and deteriorative microorganisms and modifying enzymes activities makes this technology very appropriate for meeting increasing consumer demand for minimally processed, healthier, and safer products. HPP is a postpackaging process in which a product kept in a flexible package is placed inside a compression chamber. The chamber is sealed and filled with a pressure transmission fluid (commonly water and oil) and the system is pressurized by a pumping and pressure intensification mechanism. HPP has been shown to provide efficient inactivation of vegetative microbial cells. Commonly, pressures between 400 and 800 MPa for 1 and 15 min have turned out to be effective for preserving quality and achieving microbial stability, thus providing prolonged shelf life under refrigerated conditions (Rosenthal et al. 2018). This technology has been mainly used for food preservation, although it has possibilities for other applications, such as texture modification, shift or assisted freezing, and extraction of food components (Knorr et al. 1998, Naik et al. 2013, Rastogi and Knorr 2013). Besides being used for the preservation of fresh-cut fruits, HPP has other potential applications such as pretreatment before drying and frying vegetable snacks. According to Oey et al. (2008), HPP can partially modify the cell permeability of fruits and vegetables benefiting the quality of osmotic-dried, air-dried, freeze-dried, or fried snacks. Rastogi et al. (2000) observed a higher diffusion coefficient in high pressure-pretreated pineapple cubes, showing that HHP pretreatment of vegetables can minimize the time of drying while maintaining the quality of the final products. Similarly, a study on textural changes and drying rates of high pressure-pretreated pineapple slices was conducted by Kingsly et al. (2009). These authors observed that hardness, springiness, and chewiness of pineapple slices were reduced by high pressure whereas cohesiveness was not significantly affected. On the other hand, in another comparative study of the effects of freezing or HHP as a pretreatment before vacuum frying of carrot-based snacks, Albertos et al. (2016) showed that both pretreatments caused cell modification, as observed from microstructural analyses. Pretreatment application helped in maintaining phenolic content and antioxidant

TABLE 2.2
Methods of Pretreatment of Fruits and Vegetables before FD, Drying Conditions and Effect of Pretreatment

Raw Material	Method and Conditions of Pretreatment	FD Conditions	Main Effect	References
Guava fruit	BL and ultrasounds (37 kHz, 240 W, 65°C, 5 and 10 min)	40°C, 75 Pa	Reduced DT, better color preservation, decreased TPC and AA	Alvarez et al. (2019)
Red bell pepper and strawberries	PEF, the field strength 1.0 kV/cm, the number of pulses was 20 and 200, treatment time 2.0–28.6 ms	−4±2°C and −40±2°C, 12,500 Pa, time 72 h	Reduced firmness, higher rehydration capacity	Fauster et al. (2020)
Apple	PEF, pulse duration of 40 ms and pulse width of 10 ms. The interval between the pulses 0.5 s (2 Hz). Energies of 0.5 and 1 kJ/kg and a field strength of 1.07 $kV \cdot cm^{-1}$	40°C, 100 MPa	Reduced DT, increased AA	Lammerskitten et al. (2019)
	PEF, pulses strength 1,000, 1,250, 1,500 $kV \cdot cm^{-1}$ Pulse duration 60, 90, 120 μs; pulses number 15, 30, 45	I step 70°C, 40~45 Pa, II step 90°C, 30~35 Pa	Reduced DT, increased hydration capacity	Wu and Guo (2010)
	PEF, 800 $V \cdot cm^{-1}$, 0.1 s	40°C, 1,000 Pa	Better preservation of shape, increased porosity	Parniakov et al. (2016)
Potato	PEF, electric field strength 1,000, 1,250; pulse width, pulses number 60, 90, and 120 μs, and 1,500 $V \cdot cm^{-1}$; pulses duration 500 ms	75°C, 40–45 Pa	Reduced DT	Wu and Zhang (2014)
Okra	US, 40 kHz, the power density is 25 W/L, treatment time 30 min, samples were frozen at −20°C for 24 h, then thawed by using US	Main drying at 18°C, final drying at 20°C, vacuum pressure of 52 Pa	Reduced FD time and total energy consumption, increased AA activity and lower degradation of chlorophyll	Xu et al. (2021)
Carrot	US, 45 kHz, the ultrasound power 150, 240, and 300 W, treatment time 30 min	60°C, 80 Pa	Reduced DT	Fan et al. (2020)
Red bell pepper	US, 76, 90, and 110 W	Drying temperature 50°C, 46 Pa	Reduced DT	Schössler et al. (2012)
Apple, carrot, eggplant	US, 25 and 50 W, 21.9 kHz, US 0.3, and 20.5 $kW \cdot m^{-3}$	−5, −7.5, −10°C, air velocity 2.5 $m \cdot s^{-1}$, atmospheric FD	Reduced DT, nondestructive effect on AA	Merone et al. (2020)
Sweet potato	US at 25°C, 30 kHz, power of 200, 400, and 600 W, duration 30 min	Drying temperature was 50°C, pressure 80 Pa	Reduced DT and improved color and texture	Wu et al. (2020)

(*Continued*)

TABLE 2.2 (CONTINUED)
Methods of Pretreatment of Fruits and Vegetables before FD, Drying Conditions and Effect of Pretreatment

Raw Material	Method and Conditions of Pretreatment	FD Conditions	Main Effect	References
Strawberry chips	US, 200 W, 40 kHz, duration 25 min	4°C, 10 Pa, 20 h	Reduced DT and enhanced antioxidant properties	Zhang et al. (2020)
Quince	US, 28 kHz, 50 W, time 10, 20, and 30 min	–25°C, 48 Pa	Reduced hardness and shrinkage, increased rehydration	Yildiz and Izli (2019)
Button mushrooms	US, 12.3 and 24.6 $kW{\cdot}m^{-3}$	–10°C, 2 $m{\cdot}s^{-1}$	Reduced DT and lightness, decreased hardness and chewiness, or rehydrated samples	Carrión et al. (2018)
Strawberry chips	HPP, from 0 to 250 MPa, 10 min	–50°C, 10 Pa	Increased redness, lightness, and total content of anthocyanin, reduced DT	Zhang et al. (2020)

Source: Adapted from Dziki (2020).
AA – antioxidant activity; BL – blanching; DT – drying time; FD – freeze-drying; HHP – high hydrostatic pressure; OD – osmotic dehydration; PEF – pulsed electric field; TPC – total phenolics content; US – ultrasound

capacity of the samples, an effect that could be observed throughout storage. Freezing pretreatment increased crispness and oil absorption values of the samples, as compared to HPP-pretreated or control samples. The authors concluded that the use of the proposed pretreatments (HPP or freezing) resulted in a feasible approach for improving the nutritional and organoleptic properties of vacuum-fried carrot snacks. Recently, Zhang et al. (2020) showed that HHP (50, 100, 150, 200, and 250 MPa) pretreatments significantly increased water mobility of strawberry slices which resulted in a significant reduction of drying time by 9–24%. Furthermore, the extent of HPP pretreatment increased redness values and anthocyanin contents (Figure 2.10 and Table 2.2). Higher HPP pressures increased and then decreased soluble pectins, while the contents of protopectin and cellulose decreased. After the HHP pretreatment, chromoplasts and moisture were more evenly distributed in the strawberry slices. Microscopy images showed the formation of microscopic holes or channels in the matrix and the breakdown of tissue structure after the application of HHP. Results suggested that this pretreatment disrupted the integrity of the fresh strawberry, which enhanced the drying efficiency and migration of the chromoplasts during the subsequent vacuum-freeze drying step.

Al-Khusaibi and Niranjan (2012) evaluated the application of HHP as a pretreatment prior to deep-fat frying of potato slices. The authors investigated the impact of HPP on the frying time and oil content of potato chips. The pressure ranged from low (200 MPa) to high pressure (800 MPa) for up to 5 min. It was found that high-pressure pretreatment could reduce the frying time necessary to obtain a final water content of ≤ 2%, but marginally increased the oil uptake. This might be related to higher water permeability caused by the high pressure, which enhanced oil penetration into the fried slices. Slices treated at 200 MPa for 5 min contained the highest oil content. Albertos et al. (2016) reported that high-pressure processing combined with freezing prior to vacuum frying had remarkable impacts on the final quality of fried products especially in terms of crispiness of carrot chips, susceptibility to oxidation, and retention of flavor and phenolics. The same authors explain

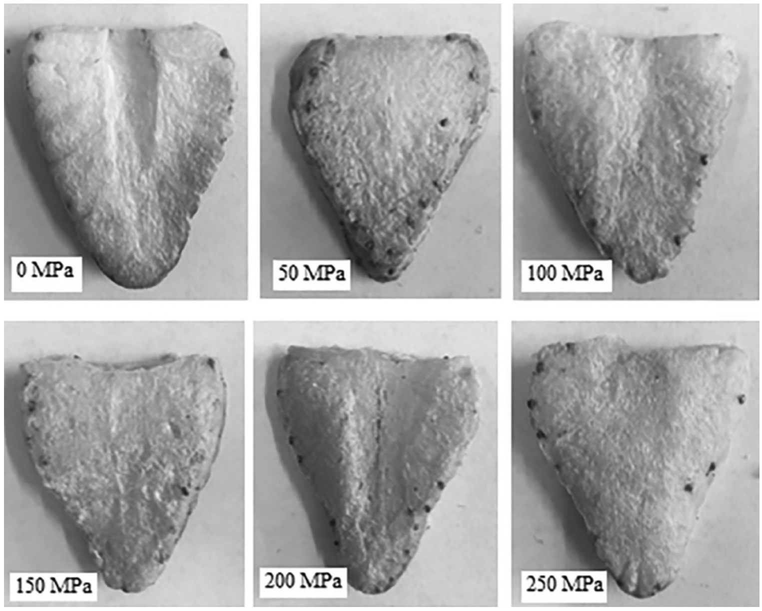


FIGURE 2.10 Effect of HHP pretreatment on color of freeze-dried strawberry chips (Zhang et al. 2020).

that HPP may probably affect color, oxidation, and enzymatic and non-enzymatic reactions during the frying process (Albertos et al. 2016).

2.3.2 Pulsed Electric Field (PEF) as Pretreatment in Snacks Elaboration

PEF processing involves the application of short pulses (μs) of electric fields intensities (E) varying from 0.1 to 40 kV/cm, depending on the pursued objective. The increase of product shelf life by the inactivation of microorganisms and enzymes is usually achieved with HIPEF (20–40 kV/cm). MIPEF (1–20 kV/cm) are commonly applied as pretreatments for the improvement/optimization of drying, frying, freezing, and extraction, among others processes (Morales-de la Peña et al. 2021, Wang et al. 2018). Likewise, MIPEF processing at low E (0.1–3 kV/cm) has demonstrated to be able of inducing stress reactions in horticultural crops generating secondary metabolites (Toepfl et al. 2006, Oey et al. 2016). During the last decades, the application of PEF has attracted large interest not only as cold pasteurization technology but also as an assisting process of well-established treatments in the food industry. Different research studies have demonstrated that the application of MIPEF as pretreatment enhances the efficiency of different processes by reducing operation time with an overall increment in extraction yields as well as nutritional and nutraceutical properties of extracted food products (Traffano-Schiffo et al. 2016, Lammerskitten et al. 2019). It has been observed that under the effects of MIPEF treatments, cell membranes may be irreversibly or reversibly permeabilized (Barba et al. 2015). According to Soliva-Fortuny et al. (2009), the effects of MIPEF have been well correlated to the more efficient recovery of high-added value compounds from different matrices, to the improvement of mass transfer rates, to the enhancement of osmotic dehydration, drying, frying, and freezing efficiency, and to the increase in oil, juice, and bioactive compounds extraction yields from different sources. In this sense, MIPEF processing has the capability of being implemented as an assisting process for diverse unit operations, thus allowing the development of high-quality products. An interesting application of MIPEF processing is to assist drying processes applied in snacks elaboration; Traffano-Schiffo et al. (2016) used kiwifruit as a model to investigate the transport mechanisms as affected by PEF pretreatments which are known to improve osmotic dehydration (OD). Kiwifruits were treated at 0.10, 0.25, and 0.40