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Mohammed Seddik Benyahia University-Jijel



Faculty of Nature and Life Sciences

Department of Applied Microbiology

and Food Sciences

كلية علوم الطبيعة والحياة

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Prepared by Dr Rima AYAD

Senior Lecturer “A”

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Ref.....

~ *Preface* ~

Food formulation strategies are essential for the product development process. Food formulation is essential for the development of new food products, in response to the growing consumer demand for products with key health and nutrition properties. It is imperative to have a clear understanding of the different ingredients, their roles, and a judicious use of the available technologies.

The development of new products and product reformulations have been implemented globally by food processors to develop innovative foods. Food formulation is perhaps one of the most important components in the process of new product development and the application of new technology in the food manufacturing sector.

Assuming basic knowledge in biochemistry, food biochemistry, and agri-food technologies, it emphasizes the recent advances in food design and formulation technology, the application of artificial intelligence in the development of new products, and in sustainable food manufacturing.

This document is primarily aimed at students preparing for their master's in food science and quality control, students of food biotechnology, as well as nutrition students, who will find a review of the basic knowledge on this subject.

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Chapter I. Food-Health: What are the definitions?

Introduction

In many parts of the world the relationship between food and health is today predominately defined by a nutritional and medical discourse. This discourse focuses on food intake as a core determinant of individual bodily and mental health, prevention of under or overweight, and of future diseases. The prominence and adoption of this discourse becomes apparent when not merely nutritionists but also television chefs, advertisers, and eaters routinely talk about food and eating employing nutritional terminology such as calories, protein, carbohydrates, vitamins, minerals, or fibre, and remark on the positive health effects of these nutrients as well as other food ingredients. Sociologists and other social scientists, however, have a broader understanding of the relationship between food and health and emphasize how cultural meanings and beliefs as well as social structures and institutions such as education, media, law, politics, and economy shape food practices). Relatedly, sociologists and many other researchers and practitioners emphasize the role that access to, availability of, and affordability of food plays.

Over the last decades, many sociologists have made important interventions to sociohistorically and socioculturally situate the close entanglement of food, nutrition, and health, have interrogated what is meant by healthy food and/or healthy eating, and have emphasized the complexity of the relationship between food and health beyond nutrition. Although many sociologists would certainly not deny that a balanced diet is important for an individual's health in general, they emphasize that eating is not simply an individual act, an issue of personal choice, or a private habit.

Thus, people's relationship to food tends to be characterized by a tension between the reasoning and calculation that can be used to improve human performance and health and the sensual, physical, and cultural aspects of food that are vital for the experience of closeness, coherence, and comprehensibility. This tension can be expressed through the terms "nutrients" and "food." The former relates to a scientific approach, the latter to a more comprehensive, culturally constructed approach. Ethnological perspectives on the role of food in human life illuminate different aspects of food, such as culture, relations, identity, and power.

Let us define and describe food, nutrition, health and fitness :

- **Food** can be defined as anything solid or liquid which when swallowed, digested and assimilated in the body provides it with essential substances called nutrients and keeps it well. It is the basic necessity of life. Food supplies energy, enables growth and repair of tissues and organs. It also protects the body from disease and regulates body functions.
- **Nutrition** is defined as the science of foods, nutrients and other substances they contain ; and of their actions within the body including ingestion, digestion, absorption, metabolism and excretion. While this summarises the physiological dimensions, nutrition has social, psychological and economic dimensions too.
- **Nutrients** are the constituents in food that must be supplied to the body in suitable amounts. These include carbohydrates, proteins, fats, minerals, vitamins, water and fibre. We need a wide range of nutrients to keep ourselves healthy. Most foods contain more than one nutrient such as milk has proteins, fats, etc. Nutrients can be classified as macronutrients and micronutrients on the basis of the required quantity to be consumed by us everyday. The figure on the next page shows us the distinction between macronutrients and micronutrients.

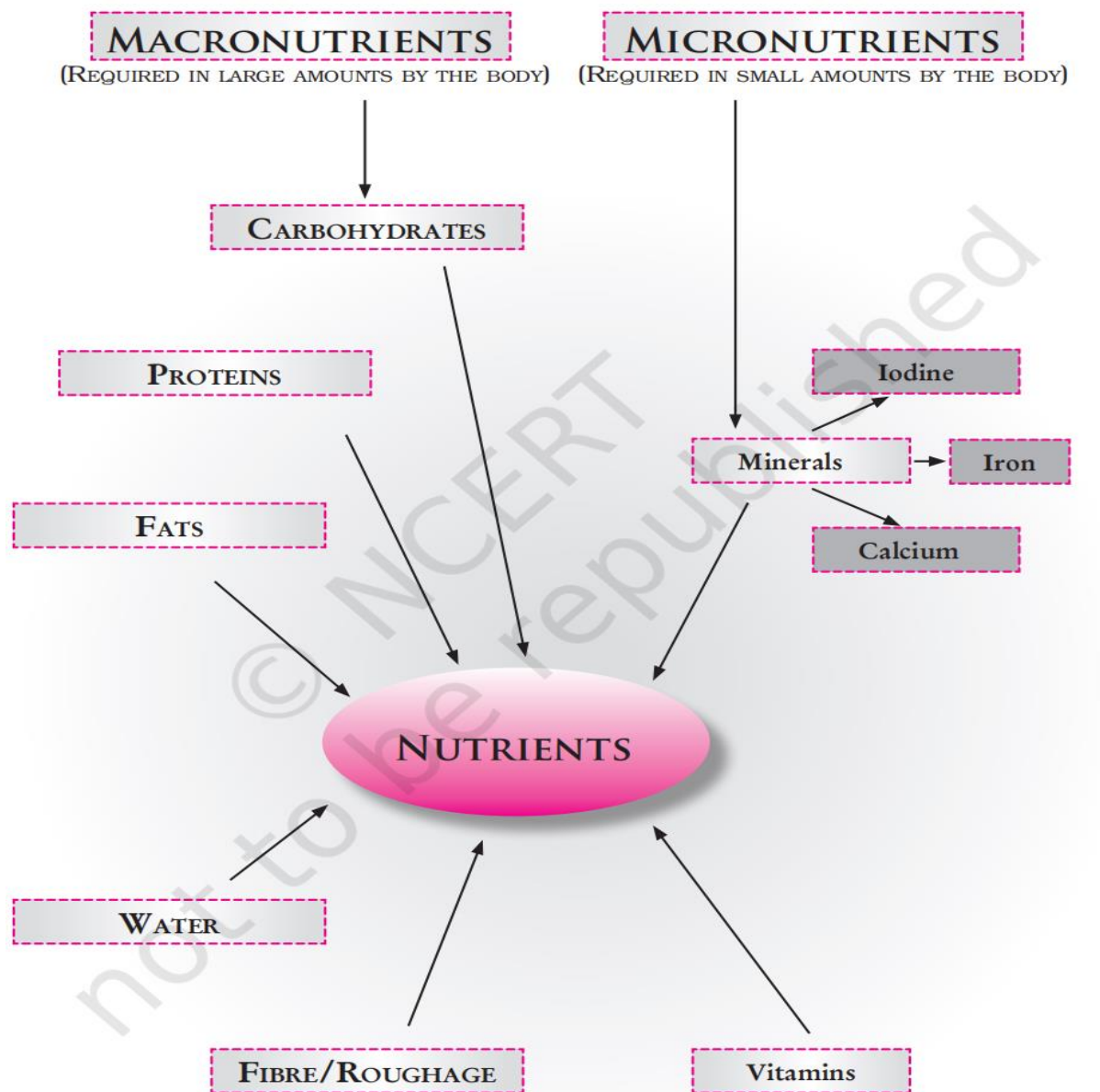


Figure 1 : Basic nutrients in our food (NCERT, 2025).

I.1. Relationship between eating behavior and health

The relationship between eating habits and the health of the population has also been an active field of research for several decades. Nutrition and health, in fact, are two sides of the same coin. They are, therefore, inseparable. Health depends to a large extent on nutrition, and nutrition depends on the food intake. So food, is the most important single factor for health and fitness.

The term « **eating behavior** » includes the physiological approach to food intake, diet (which represents the nature, quality, diversity, and quantity of food consumed and how it is prepared), and the sociocultural dimensions related to food supply, product choice, meal times, and meal structure. The terms eating behaviors, habits, and practices were used in a broad sense.

Eating behavior is usually initiated by a state of physiological energy deficit or a desire for palatable food. These motivated behaviors consist of foraging, food consumption (ingestion), and satiety that terminates eating. Eating is influenced by homeostatic (i.e., physiologically driven factors) and hedonic (i.e., reward-driven factors) signals involving the brain and the peripheral organs (**Figure 2**) and managed through executive control. Food seeking is driven by the motivational state of hunger or as a reaction to cues previously associated with food reward. Appetite and food consumption can be overstimulated by a tailored food environment that facilitates food-reward, resulting in excess food and energy consumption. Likewise, biological dysfunction in appetite regulatory pathways can contribute to a myriad of food-related pathologies ranging from anorexia nervosa to obesity.

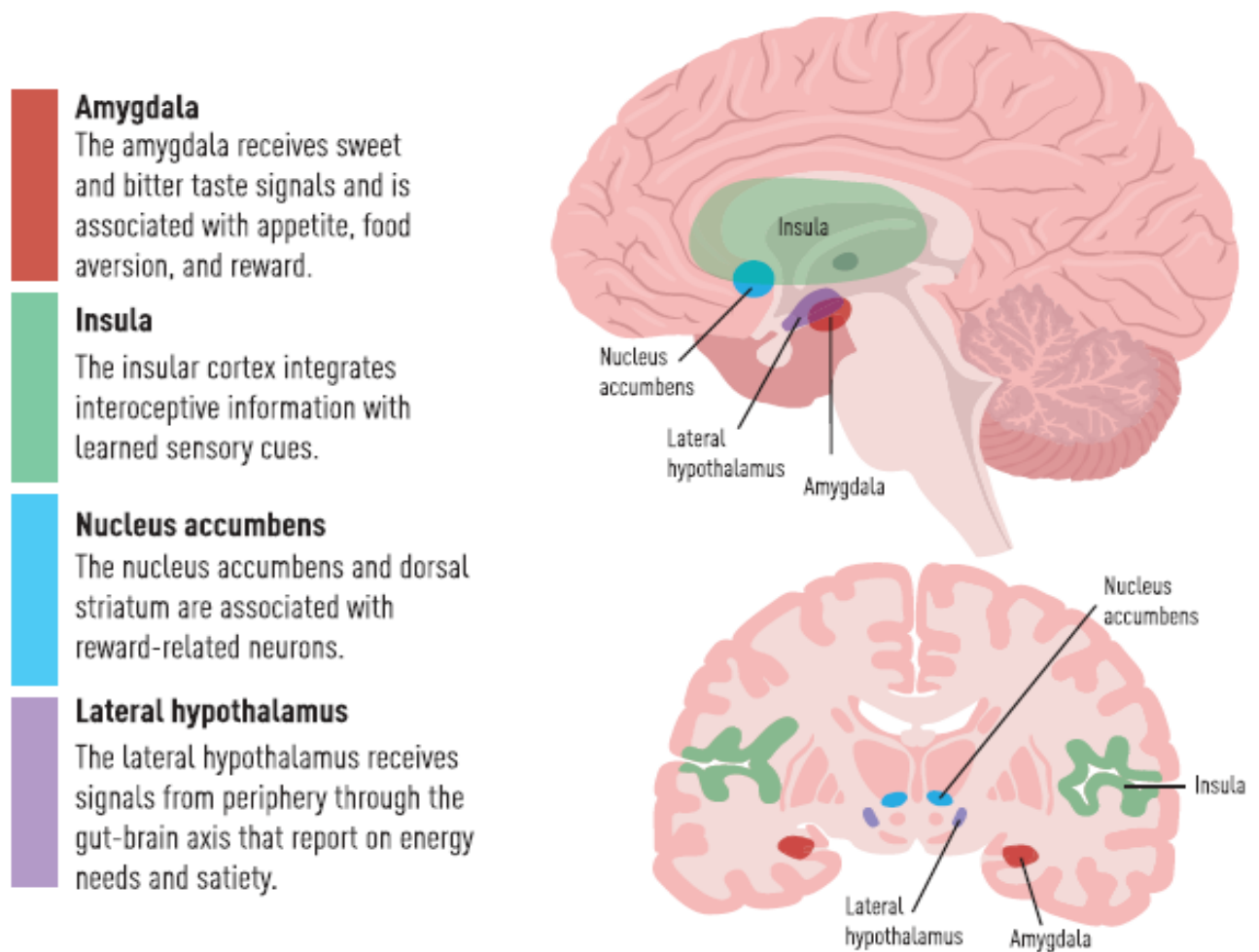


Figure 2 : Regulatory pathways of eating behavior. The hypothalamus and brain–gut axis. The nucleus tractus solitarius (NTS) of the hypothalamus senses visceral signals through the vagus nerve (Andermann and Lowell, 2017).

Knowing the nutritional composition of food is a widespread concern. Traditionally, this has been the domain of nutritionists and dietitians. But today, it is also a concern for food producers, processors, and distributors: the emergence of new, low-fat, or reduced-fat food ranges is the most obvious consequence of this. Finally, changes in eating habits over the last few decades have led to the same concern among consumers, which can sometimes escalate into anxiety. This clearly highlights the fact that nutrition education should be part of everyone's basic education.

Our bodies need energy and nutrients to function properly. Energy is used for muscle contraction (motor muscles, heart, respiratory muscles, stomach, intestines, etc.). This energy is provided by the « **combustion** » of nutrients found in food; it also consumes the oxygen we

breathe. Food is also necessary for the constant renewal of our body's components (cell renewal and growth), for cell function itself, and for the regulation and control of this function.

It is now well established that diet and nutritional status play an essential role in the development and clinical expression of the diseases that are most prevalent today in all industrialized countries, namely cardiovascular disease and diabete.

I.2. Product categories defined at the regulatory level

These include the three main product categories referred to in the usual definition of « **healthy foods** » :

I.2.1. Traditional foods

Directive (EC) No. 178/2002 of the European Parliament and of the Council laying down the general principles and requirements of food law provides the following definition of food: any substance or product, whether processed, partially processed, or unprocessed, intended to be ingested by humans.

As mentioned above, functional foods have not been defined at the regulatory level. However, this concept can be linked to several categories of products that have been defined. Thus, a functional food can be a “novel food,” an enriched food, or a traditional food that simply has a proven health benefit, in which case particular attention must be paid to the provisions relating to labeling and advertising (health claims).

I.2.2. Dietary products (products intended for particular nutritional uses)

Dietetic products or foods for particular nutritional uses are foods which, due to their specific composition or manufacturing process, are clearly distinct from everyday foods, are suitable for the nutritional purpose indicated, and are marketed in such a way as to indicate that they meet this purpose.

I.2.3. Food supplements

According to Directive 2002/45/EC of the European Parliament and the Council of the European Union, food supplements are foodstuffs whose purpose is to supplement the normal diet and which are a source of nutrients or other substances with a nutritional or physiological effect, alone or in combination, marketed in dose form, i.e., forms of presentation such as capsules, tablets, tablets, pills and other similar forms, as well as sachets of powder, liquid

ampoules, dropper bottles, and other similar forms of liquid or powder preparations intended to be taken in measured small quantities.

I.3. Balanced diet

A balanced diet is one which includes a variety of foods in adequate amounts and correct proportions to meet the day's requirements of all essential nutrients such as proteins, carbohydrates, fats, vitamins, minerals, water, and fibre. Such a diet helps to promote and preserve good health and also provides a safety margin or reserve of nutrients to withstand short durations of deprivation when they are not supplied by the diet. The safety margin takes care of the days we fast, or the short-term deficiency of certain nutrients in the daily diet. If the balanced diet meets the Recommended Dietary Allowances (RDAs) for an individual, then the safety margin is already included since RDAs are formulated keeping extra allowances in mind.

Recommended Dietary Allowances = Requirements + Margin of safety.

A balanced diet takes care of the following aspects :

- Includes a variety of food items
- Meets the RDA for all nutrients
- Includes nutrients in correct proportions
- Provides a safety margin for nutrients
- Promotes and preserves good health
- Maintains acceptable body weight for height

Good nutrition is an undeniable factor in good health. In traditional Chinese medicine, certain foods, when used correctly, serve as remedies to prevent and treat diseases. While malnutrition is a problem in developing countries, certain diseases linked to nutritional imbalances have appeared in Europe since the 1960s. When it comes to food, excess is as harmful as deprivation, and quantity must be combined with quality. Meals should be varied and include all food groups.

Nutrition is not the only factor in better health or longer life, but it is part of a set of behaviors that contribute to our lifestyle.

I.3.1. Rules for a balanced diet

I.3.1.1. Balance, variety, and moderation

A good diet is based on three simple concepts that are common sense. To stay healthy, the body needs a certain proportion of carbohydrates, fats, and proteins, as well as vitamins and minerals. Nutrition education is necessary because we are seeing a significant increase in childhood obesity in wealthy countries.

No single food contains all the nutrients we need. Different food groups are more or less rich in carbohydrates, fats, and proteins, as well as vitamins and minerals. For a balanced diet and to enjoy eating, you should eat foods from each food group every day, based on the recommended intake. No food should be completely excluded from a normal diet. The food pyramid helps us visualize the proportion of each food group that should be included in our daily intake.

I.3.1.2. Essential balances

Each individual has dietary needs that depend on their gender, lifestyle, physical activity, age, etc. A balanced diet requires a comprehensive view of what we consume. A good diet is mainly the result of regular daily meals and a varied diet. The aim of nutrition is to meet nutritional needs that change throughout life. Finding balance means listening to your body's sensations, such as hunger or lack of appetite. For a balanced diet, you need to eat three types of food :

- **Foods necessary for building** muscle mass and bone structure in our bodies. There are two subgroups: foods rich in animal protein (meat, eggs, fish) and foods rich in calcium (milk, cheese).
- **Energy-rich foods** that not only provide the energy needed for the body's cells to function, but also provide reserve substances. There are two sub-groups: foods rich in fat (butter, oil, nuts, cold cuts) and foods rich in starch or sugar (bread, pasta, potatoes, rice, sugar, jam).
- **Functional foods** that provide the fiber necessary for proper bowel function, vitamins, and minerals essential for cellular metabolism (vegetables, fruits, greens).

I.3.2. Keys to a balanced diet

I.3.2.1. Diversity : Dietary diversity refers to the daily consumption of foods from each of the different food categories : grain products, fruits, vegetables, dairy products, meat, fish, and eggs. When dietary diversity is low, it is often fruits and vegetables that are neglected.

I.3.2.2. Variety : Food variety refers to the daily consumption of different foods within the same category. Eating different foods promotes dietary diversification and therefore better coverage of nutritional needs.

I.3.2.3. Structure : The structure of meals is represented by the sequence of different dishes that make up a traditional meal (starter, main course consisting of meat or fish with side dishes, dairy product and/or dessert). It is necessary for meeting nutritional needs if this structure ensures dietary diversity and variety. People eat anything at any time and in any quantity, which exacerbates weight problems. It is difficult to reconcile simplification with a balanced diet, etc.

I.3.2.4. Density : Depending on the foods consumed, it is possible to eat a lot of low-calorie foods or a little of high-calorie foods. In the context of weight problems, it is often observed that individuals have a fairly monotonous diet that favors foods with high energy density. Adopting a diverse and varied diet is therefore already a big step forward.

I.3.2.5. Frequency : Just as no food is inherently bad, no food is inherently bad for a balanced diet or health. It's all a question of frequency or moderation: eating certain foods too often, or conversely, eating certain foods too rarely, can both have adverse effects on health.

I.4. Food pyramid

The food guide pyramid is a graphic depiction of the daily food guide (**Figure 3**). The illustration was designed to depict variety, moderation, and also proportions. The size of each section represents the number of daily servings recommended. The broad base at the bottom conveys the message that grains should be abundant and form the foundation of a healthy diet. Fruits and vegetables appear at the next level, showing that they have a less prominent, but still important place in the diet. Meats and milks appear in a smaller band near the top. A few servings of each can contribute valuable nutrients such as proteins, vitamins and minerals, without too much fat and cholesterol. Fats, oils and sweets occupy the tiny apex, indicating that they should be used sparingly.

Alcoholic beverages do not appear in the pyramid, but they too, if consumed, should be limited. Items such as spices, coffee, tea and diet soft drinks provide few, if any, nutrients, but can add flavour and pleasure to meals when used judiciously.

The daily food guide plan and food guide pyramid emphasise grains, vegetables, and fruits. These are all plant foods. Some 75% of a day's servings should come from these three groups. This strategy helps all people obtain complex carbohydrates, fibre, vitamins, and minerals with little fat. It also makes diet planning for vegetarians easier.

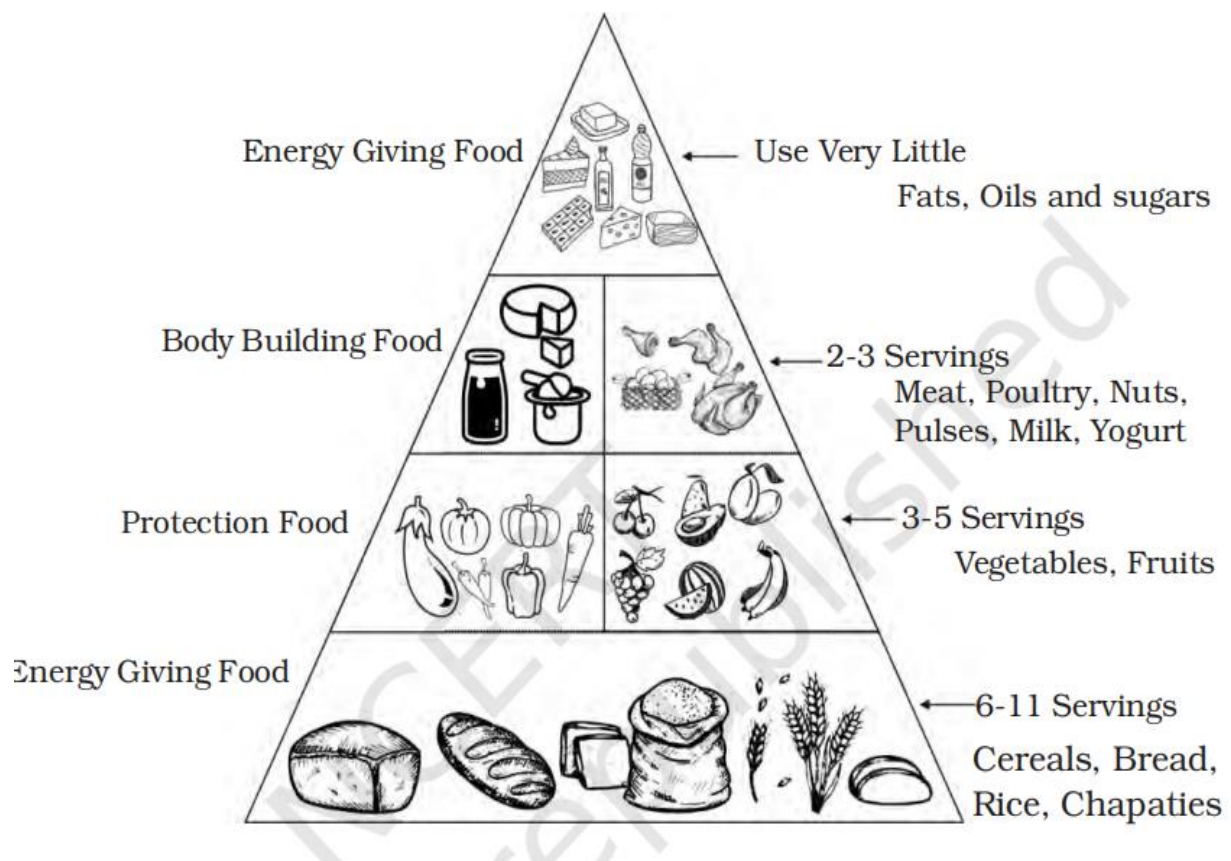


Figure 3 : Food guide pyramid (NCERT, 2025).

I.5. Basic food groups

One of the simplest ways to plan a balanced diet is to divide foods into groups and then make sure that each group is included in the meals. A food group consists of different foods which have common characteristics. These common features may be the source of food, the physiological function performed, or the nutrients present. The foods that make up the human diet can be classified into seven groups according to their chemical composition :

I.5.1. Group 1 : Water, liquids, and beverages

All beverages provide water, mineral ions, and trace elements necessary for cell function. The human body is made up of more than 60% water. It is important to drink several times a day, even when you don't feel thirsty, depending on climate-related losses and physical activity. Be careful not to consume too many sugary drinks.

I.5.2. Group 2 : Fresh fruits and vegetables

These fresh foods are rich in water, minerals and trace elements, vitamins, and dietary fiber. Vitamin C is an antioxidant that helps fight cellular aging. They have a fairly low energy value: low in fat, their sugar content varies. Because of their nutritional qualities, they should be included in every meal and it is advisable to diversify them as much as possible.

I.5.3. Group 3 : Bread, cereals, starchy foods, and pulses

This group includes bread, cereals, starchy foods (potatoes, rice, pasta, semolina, etc.), and pulses (peas, beans, lentils, etc.). These foods are rich in slow-release sugars and provide good energy value in the form of starch. They also contribute to dietary fiber, B vitamins, and minerals (iron and magnesium) intake. They should be included in sufficient quantities at every meal, as they ensure long-term energy needs are met, preventing energy slumps.

I.5.4. Group 4 : Milk and dairy products

This group includes all dairy products such as milk, cream, yogurt, and cheese. These foods provide essential proteins, animal fats, calcium, phosphorus, and fat-soluble vitamins. These foods should be included in every meal, especially for growing children and the elderly. The energy value, vitamin content, and protein content depend on the technology used in their preparation.

I.5.5. Group 5 : Meat, fish, and eggs

Foods in this group are mainly rich in animal proteins and essential amino acids. They also provide iron, which is essential for hemoglobin synthesis and immune system integrity, vitamin B12, and trace elements. They should not be consumed in excess, as they also contain fats, which can increase the risk of cardiovascular disease.

I.5.6. Group 6 : Fats

This group includes oils, butter, margarine, lard, and cream. These are energy-rich foods that should be consumed in moderation. They provide lipids and essential fatty acids, as well as

fat-soluble vitamins A, D, and E, which are essential for the proper functioning of the nervous system and cells. Fats should not be consumed in excess due to the risk of cardiovascular disease.

I.5.7. Group 7 : Sugary foods

At the top of the pyramid are foods that are not essential but are eaten for pleasure. This group includes sugary drinks, pastries, cookies, candy, honey, jam, and chocolate. All these foods are very high in calories and contain fast-acting sugars, which provide the body with readily available energy. They are not essential, even if they are a great treat for food lovers.

I.5.8. Guidelines for using the basic food groups

The seven food group system can be used both for planning and assessing balanced diets. It is a simple daily food guide which can be used for nutrition education as well. Guidelines could be adopted depending on the food groups.

- Include at least one or a minimum number of servings from each food group in each meal.
- Make choices within each group as foods within each group are similar but not identical in nutritive value.
- If the meal is vegetarian, use suitable combinations to improve the overall protein quality of the diet. For example, serving cereal-pulse combinations or including small quantities of milk or curds in the meal.
- Include uncooked vegetables and fruits in the meals.
- Include at least one serving of milk to ensure a supply of calcium and other nutrients as milk contains all nutrients except iron, vitamin C, and fibre.
- Cereals should not supply more than 75% of total Kcal/Calories.

I.6. Food intake

Food intake must respect these essential balances. It is advisable to eat three meals a day with the energy intake distributed as follows: **20 to 25%** at breakfast, **40 to 45%** at lunch, and **25 to 30%** at dinner.

The average food ration for an adult male with low physical activity is approximately 2,400 kcal/day ($\approx 10,000$ kJ). Regardless of the recommended calorie intake, it is recommended to consume:

50 to 55% of energy in the form of carbohydrates (1 g of carbohydrates = 4 kcal), 10 to 15% in the form of protein (1 g of protein = 4 kcal), or approximately 250 to 300 g per day for an adult, of which 1/5 should be in the form of fast-acting sugars (sugar) and the rest in the form of complex sugars (starch).

30 to 35% in the form of lipids (1 g of lipids = 9 kcal), or approximately 70 to 100 g per day for an adult, with a distribution between saturated fatty acids (25%), monounsaturated fatty acids (50%), and polyunsaturated fatty acids (25%).

10 to 15% in the form of proteins (1g of protein = 4 kcal), or approximately 60 to 80g per day for an adult.

This ration must provide sufficient quantities of all food groups:

- **Macronutrients** : carbohydrates, lipids, and proteins, which are sources of the energy needed to maintain and function the body ; amino acids and essential fatty acids ;
- **Micronutrients** : essential for cellular function : mineral ions, trace elements, and vitamins ; water and cellulose.

I.7. Energy requirements and intake

A person's daily food intake depends on their basal metabolic rate. This is the amount of energy a person expends when they are completely at rest, calm and awake, lying down and fasting, at a room temperature that does not require energy expenditure for thermoregulation. Basal metabolic rate is expressed in calories, kilojoules, or watts per square meter of body surface area per hour. The basal metabolic rate for men is estimated at 1778 kcal/day and for women at 1318 kcal/day.

A person's daily energy expenditure is due to their basal metabolic rate, which accounts for 60 to 70% of their total energy expenditure, plus the energy lost through muscle work, digestion, and maintaining the body's internal temperature at 37°C. Average energy requirements are calculated by multiplying the **basal metabolic rate** (BMR) by a coefficient appropriate to the person's activity level (**Table 1**).

Table 1 : Relationship between energy requirements and basal metabolic rate (**Author**).

Type of activity	BMR = 1778 (Kcal/day)	Men	BMR = 1318 (Kcal/day)	Women
Reduced activity	BMR x 1,18	2100	BMR x 1,36	1800
Normal activity	BMR x 1,56	2700	BMR x 1,56	2000
High activity	BMR x 1,78	3000	BMR x 1,64	2200
Very high activity	BMR x 2,10	3500	BMR x 1,82	2400

I.8. Adjustment of food intake

Metabolism varies from one individual to another and depends on age, gender, weight, height, physiological condition, physical activity, and diet.

I.8.1. Variations based on weight and height

Body mass is an essential factor in determining basal metabolism. In its 1986 report, the WHO proposed equations that take into account the subject's height, in addition to their age and sex.

I.8.2. Variations according to gender and age

Lean mass or muscle mass requires eight to ten times more energy to maintain than fat mass. Men generally have more lean mass than women. This explains why men's energy requirements are higher than women's. With age, fat mass increases while lean mass decreases due to muscle loss. This natural phenomenon is even more pronounced as older people become less physically active.

I.8.3. Variations depending on physical activity

Muscle work is responsible for significant energy expenditure, which is measured by oxygen consumption. The energy expended corresponds to mechanical work, but also to the body's adaptation to exertion and the increase in body temperature. When you engage in strenuous physical activity several times a week, your basal metabolic rate increases by 5 to 10% due to increased muscle mass. For example, the average energy expenditure for running is 750 kcal/hour.

Conclusion

Nutrition science is the basis for establishing practices, policies, and guidelines that promote human health, largely through understanding the metabolic and physiological responses to foods and dietary patterns. The behavioral dimension of food decisions has been addressed to some extent through targeted nutrition education programs, albeit with little success. With the increased recognition that the diet-health-disease relationship varies among individuals and subgroups as well as across the life span, there is a need to bring more precision as well as a developmental lens to nutritional guidance and recommendations. Yet, individual adherence to relatively straightforward and achievable dietary and lifestyle recommendations around energy balance remains a challenge for both consumers and health professionals.

Chapter II. Food formulation

Introduction

Foodstuffs are generally of animal or plant (and occasionally of fungal or algal) origin. Because humans evolved from hunter-gatherers, most original food products were animal and plant materials provided by nature which had been subjected, at best, to minimal processing such as peeling, butchering, and/or roasting over an open fire. Later, preservatives such as NaCl and smoking came to be used. The domestication of plants and animals led to more predictability in the food supply and, eventually, to small-scale food processing. For example, cheese was first prepared c. 8000 years ago.

Thus, food processing was originally an activity undertaken within the homestead or farm, or at least within the local community, and changed little for centuries. Apart from the logistics of the food supply which grew necessarily more complicated with urbanization, the next major leap forward in food processing and transformed food products followed the industrial revolution in the nineteenth century. At this time, the principles of factory manufacture were applied to food processing and transformation, and new technologies were developed leading to novel or improved food products. For example, the invention in the late nineteenth century by Gustaf de Laval of the centrifugal separator to separate cream and milk (**Figure 4**) revolutionized milk processing and provided a foundation for the modern dairy industry.



Figure 4 : German language advertisement for an early cream separator produced by the Alfa Laval Company (1898) (McSweeney and Day, 2016).

Food science as a discipline also evolved in the nineteenth century following the work of pioneers such as Louis Pasteur who undertook seminal work on microbial preservation and fermentation. Food science draws from many disciplines, such as biology, chemical engineering, and biochemistry in an attempt to understand better biological materials as sources of food, and processes to ultimately improve the quality, nutrition, and sensory properties of food products. Thus, food science plays a critical role in ensuring a nutritious, safe, and abundant food supply for a growing world population. Systematic investigations into a variety of food properties and compositions are often the basis for development of food products and ingredients. Nowadays, most of the food we consume has had some form of processing to transform raw materials into a myriad of food products.

Food formulation strategies are key for the product development process. It is critical in

developing new food products along with rising consumer demand for products with key health and nutritional properties. As it is imperative to have a clear understanding of various ingredients, their roles, and judicious use of technologies available.

II.1. Definition

Formulation is a common term used in various applications, with a fundamental meaning of placing a range of desired components in an appropriate manner according to a predefined formula. Food formulation can be defined as the activity of creating, designing or developing food products with an objective of providing some functionality. The functionality can range from providing additional nutritional benefits, to dietary supplementations over and above the basic function of the food.

Food formulation can be perceived as a simple concept if it includes mixing ingredients, and it could be as complex and stringent as the pharmaceutical processes to regulate the concentration of highly functional ingredients such as bioactive peptides and fatty acids.

Formulation is an industrial activity that involves manufacturing homogeneous, stable, non-toxic products with specific end properties that meet the requirements of a functional specification (CDCF) by mixing different raw materials.

II.2. Challenges in food formulations

Food formulation is a systematic, critical, complex, and commercially-oriented research process, and a great number of challenges are faced by the formulators in finalizing a formulation. Key components associated with the food formulation include :

- the identification and selection of raw materials, which is generally based on the target end product and its use ;
- the interaction of raw materials at the ingredient level and molecular level, i.e. protein–protein, protein–lipid, etc. ;
- and the application of technology depending on food components, target consumer, quality, shelf life, and cost (**Figure 5**). Cost is one of the most important factors in food formulation. From the price of the raw materials to the cost of manufacturing, everything needs special consideration. It is important to formulate a product that follows certain requirements, especially in terms of its pricing. Therefore, a clear process is required to facilitate the sharing of information, from the raw materials needed to the manufacturing technique to the packaging material.

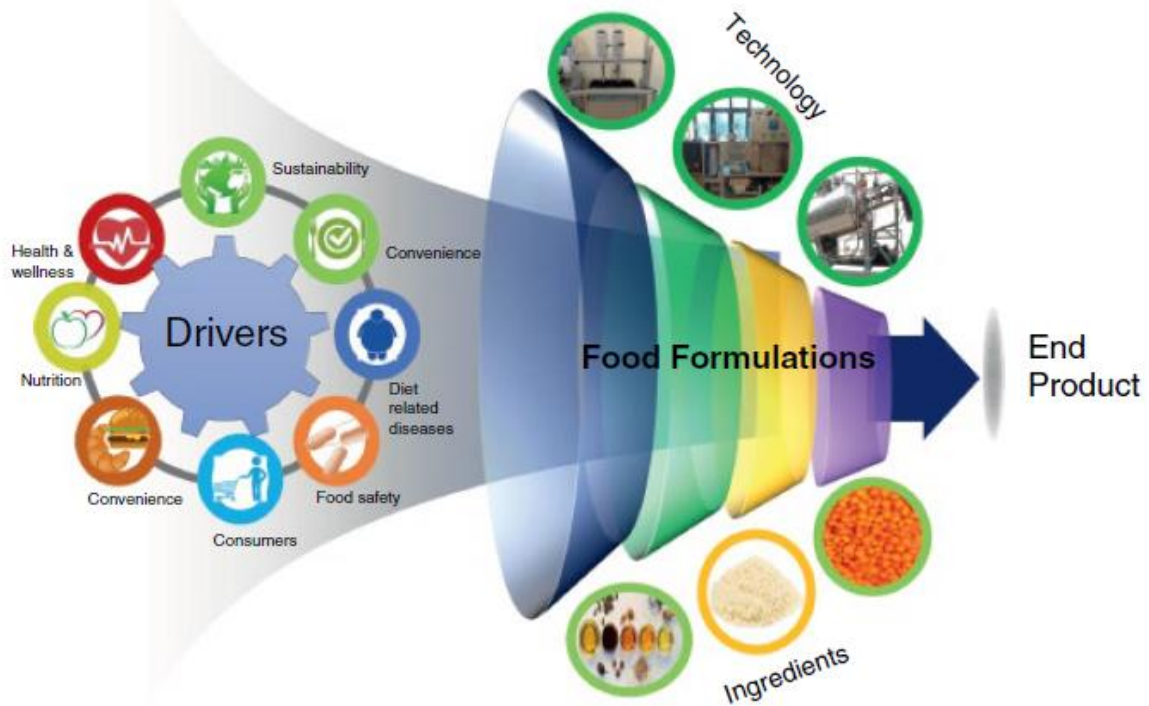


Figure 5 : Factors impacting new food formulation process (Pathania et al., 2021).

Food formulation is perhaps one of the most important and critical steps involved in the new product development (NPD) process. Food formulation irrespective of the discipline, whether in food production, culinary research and development, or formulation of nutraceuticals/pharmaceuticals, requires careful consideration of ingredient selection and the application of technologies, considering consumer demand and legislative requirements. Food products are made by combining food ingredients in specific proportions in a formulation. Research on the effects of various formulations and processes on product qualities is common. However, research is focused on the effect of either a formulation or a novel processing technique on the product characteristics. Comprehensive, documented understanding of the trends in food formulation, its effect on the commercialisation of new technologies, and the impact of new technologies on formulations is limited.

II.3. Novel foods (New product development, NPD)

The term “novel food” refers to foods or food ingredients that were not used in significant quantities before May 1997 in human food.

NPD and product reformulations have been implemented globally by food processors to develop novel foods. Novel foods are newly developed, innovative foods produced using new

technologies and production processes, as well as foods which are eaten outside of their traditional geographical boundary/region.

Novel foods could be new sources of a major food component (e.g. protein, carbohydrate, fibre) or minor food component (e.g. vitamins, minerals, enzymes), or extracts from existing food or food derived from new production processes such as UV-treated foods (milk, bread, mushrooms, and yeast). New food formulations and processing techniques have been adopted commercially for better nutrient retention, quality improvement, and shelf life enhancement, and to support sustainability.

Moreover, in recent times, consumers' attention, interest, and awareness of the health impact of various ingredients, as well as the manufacturing processes (e.g. thermal treatment) used in formulations, have grown tremendously. Health-conscious consumers have driven the increasing consumption of minimally and alternatively processed clean label products, which have been shown to fulfil tailored consumer needs for high-protein, low-fat, low-calorie products. From flavour enhancement and blocking to formulating for an ageing populace to carbohydrate systems for weight management, the future focus is on ingredients that promote better overall health. Thus, there is a requirement for detailed industrially relevant information concerning novel food ingredients and their application in the formulation of novel and health-promoting food products. In addition, industrial adoption of novel processing techniques is in its infancy ; however, some technologies have seen commercial application.

II.4. Quality criteria

The development or launch of new products involves three phases:

- Defining the quality criteria that the product to be developed must meet;
- Developing the product and verifying that its quality criteria are maintained throughout its chosen lifespan;
- Verifying these same criteria in industrial scale conditions.

II.4.1. Basic criteria

II.4.1.1. Absence of toxicity

Consumers have become more aware of what they eat, where it comes from, and how the ingredients in food affect their healthy lives. They actively seek products with natural claims and consciously check the ingredient lists of the food products.

Ensuring the absence of toxicity in food formulations involves rigorous evaluation of

ingredients, including additives, processing aids, and packaging, to ensure they do not cause adverse health effects (e.g., allergies, chronic toxicity) at consumption levels. Safety is established using toxicological data to set Acceptable Daily Intake (ADI) levels and the **threshold of toxicological concern (TTC)**. The industry is shifting toward "clean-label" alternatives to minimize synthetic chemical risks, although natural ingredients also require scrutiny.

II.4.1.2. Consistency in attributes

Taste, texture, aroma, freshness, and presentation - are paramount for building customer trust, loyalty, and satisfaction, ensuring the same high-quality experience. Customer loyalty is vital for the ongoing success and sustainability of a business. Customers who are loyal to a brand are more likely to interact with it and make repeat purchases from that brand than from one of its rivals. When a consumer has a pleasant experience with you, loyalty develops naturally and helps build trust. The degree to which a consumer is satisfied with a business, service, or product also affects their view of it. Customer loyalty is a collection of behaviors individuals engage in to show their steadfast allegiance to a product, service, or brand. Making more purchases or choosing the brand over a competitor are two examples. So consistently delivering high-quality food drives repeat business and enhances brand reputation, while inconsistency leads to negative reviews, lost patrons, and reduced profitability.

II.4.2. Verification of food quality criteria

Verification of food quality criteria involves systematic, science-based checks—including microbiological testing, sensory evaluation, and chemical analysis—to confirm that products comply with safety standards, regulatory requirements (like EFSA or FDA), and specifications. Key methods include HACCP plan audits, environmental monitoring, and testing for pathogens/contaminants.

Many attempts have been made to define food quality. One of them is based on the theory of a multidimensional set of features that can be objective (measurable, taking into account research results) or subjective (immeasurable, taking into account the opinion of the consumer). A universal definition of quality has been proposed in an international standard on quality management: “Quality is the degree to which a set of inherent properties meets the requirements”. This definition can also be applied to food, and the requirements mentioned here can be both requirements contained in legal acts and consumer requirements. Food product quality is a concept that corresponds to a set of many attributes (e.g., product specific

features, product safety, acceptance by the consumer).

One of the attributes of food quality is its authenticity. Food authentication and traceability are current topics in the food sector since they enable food quality and safety control. According to researchers, the authenticity of the product is understood as confirmation of the requirements for ensuring quality, composition, safety, usability, brand, and origin along with the information/declaration provided to the consumer by the manufacturer. It determines whether the product is really what the manufacturer declared.

II.4.2.1. Ingredients

Food formulation involves selecting and combining ingredients - macronutrients (proteins, fats, carbohydrates), water, and additives - to achieve desired taste, texture, stability, and nutritional value, while minimizing costs. Key ingredients include preservatives, flavor enhancers, emulsifiers, stabilizers, thickeners, and sweeteners, which can be natural or artificial.

While many raw materials and traditionally processed food products are widely used as ingredients in formulated foods (e.g., the use of chopped nuts or butter in baking), the modern food industry has developed a wide range of specialist ingredient products (e.g., demineralized whey powder, milk protein concentrate, various modified starches) which are now of great commercial importance in business-to-business transactions. These ingredients can be found in a huge range of formulated food products but are often unknown to the consumer as they are generally not available in retail outlets. Such ingredients can be from animal or plant origins.

- **Need for healthy ingredients**

With health and wellness trends continuing to rise and consumer preferences moving towards more natural and functional food products, offering healthy ingredients is a hot topic for the food industry. Manufacturers are under increasing pressure to alter the composition of processed foods and improve the nutritional profile of their products whilst maintaining the taste and quality. This can be done through the reduction and elimination of ingredients such as sugar and salt that cause concern or the addition of healthy ingredients to create nutritionally-enhanced or functional foods. The key requirement for healthy ingredients is to improve diets and help reduce the prevalence of diet-related disease in the population.

The food industry's response to increasing consumer awareness and the growing demand for

healthier food products has been to reduce or replace the sugar and salt content using clean label alternatives/ replacers, which will be discussed in detail in this chapter. To ensure a competitive edge, food manufacturers are also seeking new opportunities to fortify and enrich their products, whereby existing nutrient contents are increased and/or ingredients with potential beneficial health effects are added to enhance food products.

Selecting the most appropriate healthy ingredients is highly dependent on what is motivating the product reformulation. For example, is it to reduce levels of unhealthy ingredients or is it the development of functional foods, which provide the consumer with specific health benefits, or is it creating products for people with specific dietary needs (e.g. the avoidance of particular allergens) ?

A key driving force in the application and inclusion of new and exciting healthy ingredients by manufacturers is the steady stream of emerging innovations from ingredient suppliers. Understanding, characterizing, and optimizing the functionality of these ingredients is essential to deliver enhanced, healthier products with broad consumer appeal.

II.4.2.2. Organoleptic acceptance of the product

The "organoleptic" characteristics of a food product are a combination of appearance, aroma, taste and texture. Consumers are often attracted by the appearance of a food well before they have tasted it (e.g., the picture on the front of the food packaging) and tend to like a variety of choice with regard to the organoleptic properties of their foods. As a result, food production businesses tend to spend a great deal of time and money on new product development activities including market analysis, product creation/formulation, product sensory assessment and consumer taste panelling.

Reformulation and adjustment of processes can also be a challenge to the food business when seeking to "cost reduce" products in order to make them more profitable. Often the challenge is ensuring that the product organoleptic performance is not reduced beyond acceptable limits, while changing the recipe/process to facilitate the use of less costly ingredients (or use a smaller amount of the more expensive ingredients).

II.4.2.3. Physicochemical and microbiological criteria

Physicochemical and microbiological criteria in food formulation are critical, scientifically established parameters that define the safety, quality, and stability of a food product. They dictate acceptable limits for nutrient content, pH, water activity (*aw*), and pathogen levels

(e.g., *Salmonella*, *Listeria*), ensuring compliance with food safety regulations. These standards guide raw material selection, processing techniques (e.g., thermal treatment), and shelf-life determination.

II.5. Food development

The objective of the European Food Safety Authority (EFSA) is to ensure consumer safety with regard to :

- The potential toxicity of the product;
- Any nutritional imbalances caused by its introduction into the overall diet.

II.5.1. Nutritional approaches

Nutritional quality is the ability of food to nourish well. Two aspects can be distinguished:

II.5.1.1. A quantitative aspect

This is the energy stored in chemical form, provided by food to the physiological machine and measurable using a calorimeter. Consumers may seek out high-energy foods (sports nutrition) or, conversely, low-calorie foods (diet products), depending on their needs.

II.5.1.2. A qualitative aspect

This refers to the search for nutritional balance in food in relation to the needs of the consumer (human or animal), or enrichment with a particular element (vitamins, iron, etc.), or even a special composition that meets certain pathological requirements, such as salt-free or gluten-free foods (dietary products).

II.5.2. Toxicological approaches

The non-toxicity of food is an absolute safety requirement. Food must not contain any toxic elements in doses that are dangerous to the consumer, and the assessment of these doses must take into account the amount and frequency of consumption. The cause of food toxicity may be chemical (heavy metals, nitrates, etc.) or bacteriological (toxins).

II.6. Specifications

II.6.1. Definition

The functional specifications (FSS) are a document that allows the requester's needs to be precisely formulated. The FSS is a dashboard that defines the project and details the conditions under which it must be carried out; it describes all the characteristics expected of the service functions. It is the link between the company and the customer.

Before imposing a solution, it is necessary to consult with the requester in order to arrive at a solution in a structured manner. The goal of a project is to satisfy a need. The objectives of a project must be clearly stated in order to avoid any confusion between the company and the requester. This need must be expressed at the start of the project. It is a matter of explaining the fundamental requirement that justifies the design of the product.

II.6.2. Objectives

The functional specifications must:

- explain the customer's need;
- promote dialogue between the various partners in order to obtain the most effective design and implementation from the service provider;
- facilitate the choice of technical solutions proposed subsequently.

II.6.3. Food characteristics

When formulating a food product, it is necessary to determine the objectives to be achieved and express them in the form of specifications. This means that the food and its packaging must be defined in relation to various characteristics that can be grouped into categories: mainly nutritional, organoleptic, and microbiological.

All these characteristics must be translated into quantifiable criteria. This is made possible by the use of analytical techniques (**Table 2**).

Physical or sensory analysis techniques can be used to specify the organoleptic properties of a food product. These techniques make it possible to express all the characteristics of the food product in numerical values, thereby enabling criteria to be established that will form its specifications.

Table 2 : Examples of techniques used to characterize food (**Author**).

Characteristics	Technique	Criteria
Organoleptic		
Texture	Rheology	Viscosity, hardness
Color	Colorimeter	Labo parameters Detection threshold
Taste	Sensory evaluation	No difference
Microbiological		
Alteration	Predictive microbiology Challenge test Count	Nature of the germ CFU/ g
Sanitary	Research Identification	Absence or presence
Nutritional	Chemical dosage	Nature of the nutrient Quantity

II.6.4. Essential criteria and secondary criteria

In practice, in order to establish the specifications for the formulation, it is essential to set a reference product. For example, a standard such as a traditionally manufactured product or a competitor's product may be chosen.

Once the reference has been characterized using the techniques listed in **Table 2**, two categories of criteria are generally defined :

II.6.4.1. Essential criteria to be met in order to validate the design

This may involve a preference test compared to a competitor's product or the results of a challenge test on a pathogenic germ. For example, if the product must contain chocolate (risk of salmonella contamination) and water (risk of growth), the acceptance criterion may be set at a salmonella multiplication below a certain threshold during the product's shelf life.

II.6.4.2. Secondary criteria

The launch of the product is not automatically called into question if the secondary criteria are not met. For example, it may be acceptable for a pastry to lose its softness after four months of storage, even though the desired best-before date is six months, because the product will be consumed within the first two to three months.

II.7. Constraints

II.7.1. Regulations

Regulations provide a framework which, although useful, clearly limits the possibilities in terms of formulation. In fact, there are two levels of regulation: those that concern manufacturing conditions, particularly authorized ingredients, and those that concern the finished product.

II.7.1.1. Case of additives

Additives are substances that are added to food for technological purposes : to improve preservation, reduce oxidation, color food, enhance flavor, etc. Even though they are used in small quantities, these substances are evaluated and monitored to prevent adverse health effects.

Their use is therefore regulated and their presence must be indicated on the labels of the products concerned. There are different categories of additives, the five main ones being:

- Colorants;
- Sweeteners;
- Preservatives;
- Antioxidants;
- Texturing agents.

A new additive may only be used after:

- An opinion has been issued by the European Food Safety Authority (EFSA);
- An opinion has been issued by the European Commission's Standing Committee on the Food Chain and consultation with the Council and the European Parliament;
- A regulation authorizing its use has been published in the Official Journal of the European Union, specifying the conditions of use (doses and foods in which it may be used).

The conditions of use for additives will be revised based on the conclusions of the European Food Safety Authority.

II.7.2. Manufacturing conditions

Regulatory requirements are a set of constraints that must be understood before starting formulation tests, but it is equally essential to define the physical constraints that the product will be subjected to. Constraints inherent to the manufacturing process: at this stage, it is necessary to consider the constraints related to the equipment and work organization already in place in the factory.

II.7.2.1. Manufacturing process

The manufacturing process has a significant influence on food quality, whether in terms of organoleptic, nutritional, or microbiological properties. In fact, experience often shows that a formulation that meets specifications when the product is manufactured in the laboratory requires modifications when applied on an industrial scale. This is known as “scale-up” problems."

Example 1

The rheological behavior results for two sauces made from the same formulation but manufactured under different conditions show that the transition to an industrial cooker results in a significant loss of viscosity, which can be explained by the much more intense shearing than at the cooking stage.

Therefore, if the desired texture for the sauce is that of the sauce made in a saucepan (kitchen stage), it is essential to modify the formulation, in particular by changing the type of thickener or increasing its dosage.

This example illustrates the problem of **mechanical constraints**.

Example 2

Consider, for example, two vanilla dessert creams, one formulated with natural flavoring and the other with artificial flavoring.

A sensory test carried out by a panel of 17 people (**Table 3**) shows that the perception of vanilla is much stronger in the cream formulated with artificial flavoring, which could therefore be retained for the final formulation, but the cream must be sterilized.

Table 3 : Results of paired tests conducted on vanilla dessert creams (**Author**).

	Natural flavoring	Artificial flavoring
Without sterilization	3	14
With sterilization	13	4

The same sensory test is performed on both creams after heat treatment, and we see that the trend has reversed and that the natural aroma should ultimately be retained.

These two examples highlight the importance of taking into account all the constraints related to manufacturing conditions :

- Process constraints themselves, particularly mechanical and thermal constraints, such as the phenomenon of oxidation linked to the incorporation of air, which will be all the more significant as the mixing operations are important,
- Scale transfer constraints : such as the existence of waiting phases in many industrial manufacturing processes, which must be taken into account.

Conclusion

Food formulation strategies are key for the product development process. Food formulation is critical in developing new food products along with rising consumer demand for products with key health and nutritional properties. As it is imperative to have a clear understanding of various ingredients, their roles, and judicious use of technologies available.

The development of healthy ingredients and replacers is dominating the food industry and claims around the functional advantages of food products are increasingly expected by consumers who desire to feel benefits from the food they eat. The future in terms of ingredient development and application is exciting, but not without significant challenges for ingredient companies and food manufacturers.

Chapter III. Product development

Introduction

Product development has been a major activity in the food industry for over 40 years, but only gradually has it developed as a strategic business area and also as an advanced technology. For a long time it was essentially a craft, loosely related to the research and engineering areas in the company. The pressures for product development came very strongly from the needs of the growing supermarkets for a constantly changing, extensive mix of products and for continuous price promotions. So there was the drive for product difference, including minor product changes sufficient to distinguish products on the shelves, and for cost reductions. There were also underlying social and technological changes which caused major product development ; for example the increasing number of working women which sparked the need for convenience foods and eating out, and the development of spray and freeze drying which was the basis for instant foods.

III.1. Product adaptation

III.1.1. Definition

The adaptation of the domestic product for foreign markets involves offering a product tailored to the tastes, preferences, and specific needs of the targeted foreign consumers. The extreme position of adaptation would involve modifying the product so much that it would be completely new.

Adaptation can a priori concern all the characteristics of the product (name and denomination, design, packaging and labeling, brand, etc.).

Product adaptation means that the company, in its pursuit of profitability, opts for maximizing sales rather than minimizing costs.

Apart from a few products, for which there is some standardization of tastes or for which the segmentation criteria are international, the product adaptation policy remains predominant. This strategy will be adopted if sales forecasts justify the cost of adapting the product. Generally speaking, it is important to distinguish between technical adaptations and commercial adaptations.

III.1.2. Technical adaptations

Technical adaptations concern all the mandatory minimum product adaptations that the company must comply with to obtain the "release for consumption" of its product. Regulatory adaptations are imposed by law and by public authorities and condition access to a

market. Failure to comply with a technical regulation or standard related to a market makes it impossible to penetrate that market.

Technical adaptations of the product also include structural adaptations related to geographical and climatic characteristics, religious norms, language differences, etc.

III.1.3. Commercial adaptations

Commercial adaptations are of a marketing nature. They reflect the consideration, at the supply level, of consumer expectations and the sociocultural aspects of the foreign market, depending on the chosen positioning.

The company can refuse this marketing adaptation: it is left to the company's discretion, unlike technical adaptations. However, commercial adaptations are a determining factor in commercial success.

These adaptations are related to the following economic and sociocultural aspects of the targeted foreign consumers:

- consumption habits;
- preferences and tastes;
- income level (which influences the frequency of purchase but also the packaging size);
- education and literacy level (which influences packaging and labeling).

III.1.4. Advantages and disadvantages

The essential advantage of adapting a product is the associated probability of increasing sales and revenue thru better alignment with the specific needs of the targeted foreign market. In doing so, the company's profits are likely to increase, provided that the revenue generated by product adaptation is greater than the adaptation costs.

However, the company that adopts a policy of adapting its product offerings in each foreign market must ensure that strategies across these markets are harmonized to prevent policies used in one market from undermining results in others. Ensuring this cohesion is a real challenge for a company that adapts its product in each market. Moreover, the organization and implementation of a product adaptation policy across all foreign markets are quite complex.

III.2. Product standardization

III.2.1. Definition

The company that applies a standardization policy for its product offers a unique version of a product (the product sold on the domestic market) across all its foreign markets.

In its pursuit of profitability (which depends jointly on costs and sales), the company that opts for standardization of the offering prioritizes a cost minimization strategy. The standardization of the product can be done on several of its components : for example, in terms of product design or its packaging (e.g., multilingual packaging).

The standardization of the product can be modulated with a standardized or adapted communication policy:

- **A standardized product and communication :** correspond to the offering of a perfectly identical product (example: Coca-Cola). This is the simplest strategy for an exporting company, which then offers the same product in all its foreign markets with the same communication campaigns and promotional arguments as those used in the domestic market;
- **A standardized product and adapted communication :** correspond to the discovery of new uses for the product (example: bagged soups sold as soups in Europe and as sauces in the United States). As part of this strategy, the company exports an absolutely identical product but whose use and function are different from those for which it was initially designed. The only costs incurred by this approach are related to the identification of the different functions of the product and the adaptation of the communication strategy according to the new uses identified. This low-cost strategy also allows for the extension of the life cycle of a domestic product and thus the discovery of new outlets for a product that has reached maturity in the domestic market.

Generally, it is not possible to completely standardize one's products in foreign markets. Indeed, despite the potential benefits of standardization, there are significant obstacles related to foreign markets (climate, local consumer culture, income level, legal constraints, etc.) that prevent the adoption of such a strategy.

III.2.2. Advantages of standardization

The three main advantages generated by product standardization are as follows:

- cost savings
- consistency with consumers
- simplification of planning and control

III.2.2.1. Cost savings

- **Economies of scale at the production level.** By offering the same basic product in different markets, the company can achieve economies related to mass production and storage.
- **Economies in communication.** Even when the communication policy is tailored to each market, the company can generate economies of scale in communication when its products are standardized. Indeed, communication tools such as corporate documentation and advertising are more likely to be similar across markets when the product is identical.

III.2.2.2. Consistency with consumers

Thanks to the standardization of its product, the company can benefit from a homogeneous and consistent brand image across markets. This homogeneity of the offering is particularly important to maintain the loyalty of "multinational" consumers. This new type of consumer, extremely mobile and having privileged access to other markets thanks to the development of means of transport (airplanes, etc.) and new information and communication technologies (TV, Internet, newspapers, etc.), demands products whose performance is standardized from one market to another. The company that exports products likely to be purchased and consumed by these "multinational" consumers must take their requirements into account.

III.2.2.3. Simplification of planning and control

A product standardization strategy is much less complex to implement and becomes operational very quickly.

III.2.3. Disadvantages of standardization

The standardization of a product, despite the economies of scale it generates, can nevertheless lead to failure. Indeed, this strategy does not take into account the differences in cultures, tastes, needs, purchasing power, etc., of consumers from different markets. The company that adopts this strategy risks offering the "lowest common denominator" which ultimately satisfies no customer. It does not take into account the differentiation strategies of local competitors, nor the possible changes in the markets. In doing so, its commercial effectiveness risks being diminished and the generated sales volumes may not be satisfactory.

III.3. Product development

III.3.1. Laboratory /kitchen formulation

The engineers involved in formulation seek to develop new products by relying on the relationships between molecular structure and technical function (coloring, thickening, flavoring, inactivating microorganisms, etc.). The product is obtained after numerous trials; the preparers assist the specialists in this work by weighing the components of the different formulas.

The composition is generally associated with a carrier (often liquid, sometimes solid) consisting of foodstuffs and/or additives, according to the constraints related to the destination food product, while respecting consumer safety.

III.3.2. Pilot formulation

The application allows for the evaluation of the destination food product. For this implementation to be realistic and relevant, it is necessary to use the product as it will be sold to customers, that is, after any necessary transformation. This application stage at the manufacturers involves the development of food products under conditions similar to those of the industrial client. The test food thus obtained is then analyzed in terms of its organoleptic (= sensory) and sanitary qualities. To meet the client's expectations and regulatory requirements, the food must maintain its qualities, the food must retain its aromatic qualities and present all the safety guaranties both before and after processing. The two steps, formulation and application, are repeated as many times as necessary, until the desired result in the food is achieved.

III.3.3. Industrial formulation

Constructive exchanges between teams of specialists and applicators allow for the development of a product with the desired olfactory and gustatory qualities and technical characteristics adapted to the manufacturing process and the composition of the food it is intended for. This final product, controlled from a sensory and health perspective, possesses all the required qualities and safety guaranties; it can then be offered to the client. The food products, once composed, formulated, and controlled, are produced on an industrial scale, according to the client's demand. They are then sold to the food industry with accompanying documents. These documents provide complete information to the industrial user regarding the nature of the product and its conditions of use (expiration date, destination, dosage, etc.). The necessary elements for informing the end consumer are then mentioned on

the label of the finished food product and determine the sales denomination of the products. At each stage of product manufacturing, industrialists implement different types of control to ensure the organoleptic (= sensory) and sanitary quality of the product.

III.3.4. Role of macromolecular interactions

The molecular and colloidal dispersions of biopolymers and their complexes make up the structure of most foods. The structure, rheology, and other physico-chemical properties of foods, as well as their sensory characteristics, are fundamentally governed by the major biopolymers in foodstuff.

Proteins occur as structure and texture-macromolecular modifiers in foods, where multiple interactions with the rest of the biopolymers can take place. The structure, rheological, and other physico-chemical properties of many processed and convenience foods are determined to a large extent by the behaviour of the protein and polysaccharide components. The authors also found the interaction between these biopolymers within the food system to be of great interest.

Water and lipids, with their ability to bind to other components and act as solvents, are also considered important factors. The functional properties of foods reflect the physico-chemical properties of both the complexed and the individual macromolecules. This is because the complexed molecules obtain new properties as compared to the individual macromolecule. Therefore, the diversity of the food structures is contributed to by the interactions between macromolecules.

The interactions of macromolecules in food systems are not specific in nature and occur during many stages of food handling and processing. These processes facilitate unfolding of the macromolecules, a prerequisite for the interactions. The chemical and enzymatic reactions also lead to altered intra- and intermolecular interactions, which at the macromolecular level are reflected in conformation changes, complexation, and aggregation. The interactions may also result in the formation of colloids and 3D networks, which are essential in the development of macroscopic structures like suspensions, foams, emulsions, gels, and others.

Consequently, in processing of food and food products comprising either two of the three macromolecules, it is advisable to understand the potential behaviours of interactions of these macromolecules within a real food matrix. Macromolecular interactions highly influence the

food quality therefore it is of immense importance to improve our understanding of macromolecular interactions in foods. To maintain the palatable properties and bioactivity in food products, interactions between the bioactive molecules and other food components, including macro- and micro-components, needs to be curtailed.

These interactions vary in nature and can be physical, chemical, or a combination of the two. Physical interactions between ingredients could involve changes in adsorption, absorption, drying, evaporation, and particle size properties. Physico-chemical properties and interactions pertain to formation of gels, emulsions, foams, etc. Chemical interactions may be dependent upon the composition of the food including proteins, amino acids constituents, and concentrations of individual components. They may also include interactions between the food and external surfaces such as packaging material.

The intensity of chemical interactions is also dependent upon external physical conditions such as temperature, pH, moisture, and time duration of the process. The interactions and their intensity may either be desirable or undesirable, depending upon the food application and end product required. For example, the Maillard action is a chemical carbonyl– amine reaction leading to browning in egg whites which is undesirable ; however, the same reaction is favourable in baking for generating aroma, colour, and visual effects.

III.3.5. Types of macromolecular interactions

Most of the foods and food products contain all the macromolecules, though some macromolecules can be present in large or very little amounts. Complexation may take place within a type of biopolymer (e.g. protein–protein) or between different types of biopolymers (e.g. protein–lipid, protein–carbohydrate). The interactions taking place within the same type of macromolecules are termed intramolecular interactions and those taking place between different types of macromolecules are termed intermolecular interactions. The interactions may also be binary (occurring between two macromolecules) or ternary (occurring between three macromolecules). The classification and various types of macromolecular interactions are displayed in **Figure 6**.

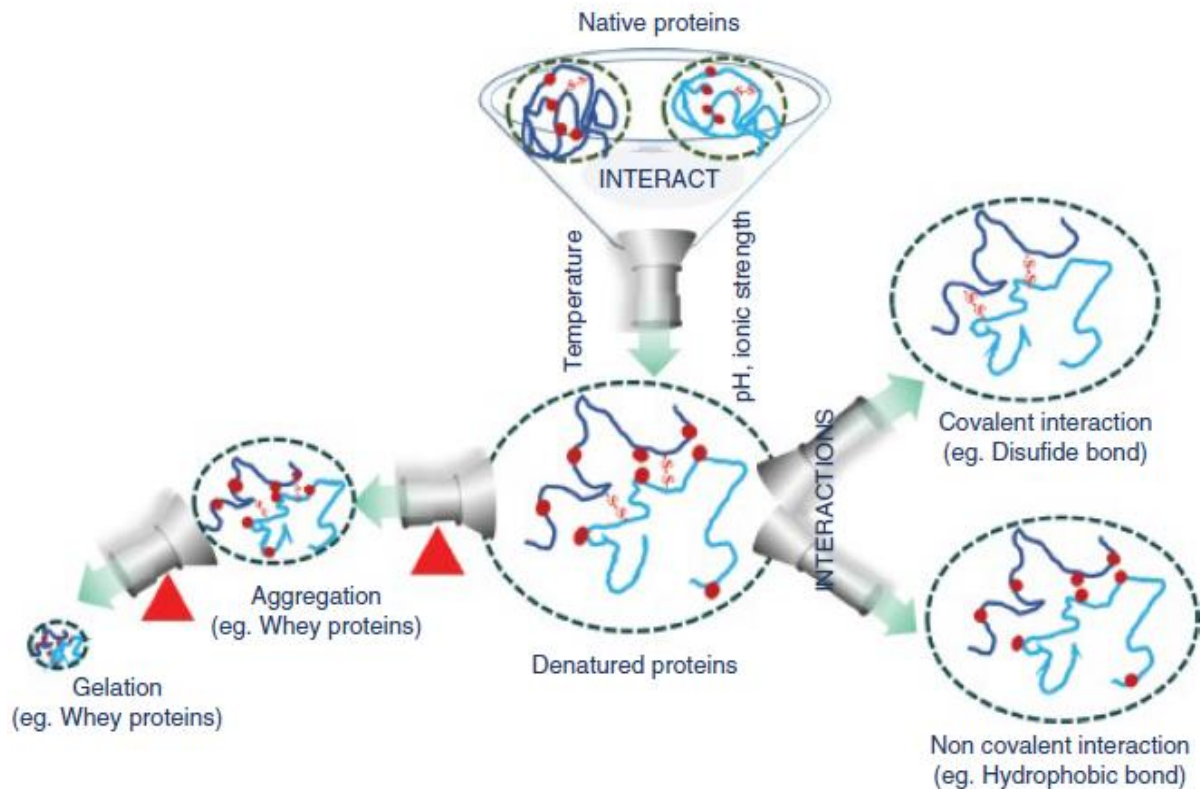


Figure 6 : Illustration of heat-induced changes in native protein structures. Formation of interactions (covalent and noncovalent in dairy proteins), right side of figure. Severe heat treatment to protein (whey) solutions inducing denaturation, aggregation, and gelation/ excessive thickening, left side of figure (**Pathania et al., 2021**).

III.3.6. Physicochemical mechanisms involved and formulation/process interaction

The physicochemical mechanisms in food include reactions such as the Maillard reaction and oxidation, as well as physical transformations like changes in color and texture. The interaction between the food formulation (ingredients) and the process (cooking or preservation methods) is fundamental because the process influences the physicochemical reactions, which in turn affect the final properties of the product (taste, color, shelf life, etc.). For example, the heat of the process triggers chemical reactions, while processes like lyophilization modify the hydration properties of the product.

In the process of food preparation and preservation, there are human actors, but there is also chemistry and biology. The preservation stage, for example, aims to delay the oxidation of fats that causes rancidity, and above all to prevent the growth of bacteria, fungi, and other

microorganisms. Further upstream, an unsuspected number of chemical reactions occur during the food transformation process.

III.3.6.1. Maillard Reaction

In this long and complex transformation process, we must not forget the physicochemical aspects. Let's take the example of baking a cereal product (biscuit, cake).

This cooking involves a chemical reaction called the "Maillard reaction," which is characterized by a succession of chemical and biochemical transformations, at the end of which the well-known brown color of biscuits, but also sauces, etc., is generated. The result will depend on the formulation of the starting product and how we provide the energy to transform the product. Analytical chemistry allows for the identification of the different stages of the Maillard reaction. It is indeed possible to monitor, during the cooking process, the evolution of a certain number of molecules, including those that are released into the atmosphere in equilibrium with the product. We can also identify the presence of newly formed molecules. By choosing one or more "marker" molecules, we can monitor the progress of the cooking, and in particular identify the molecules that are generated throughout the process (**Figure 7**).

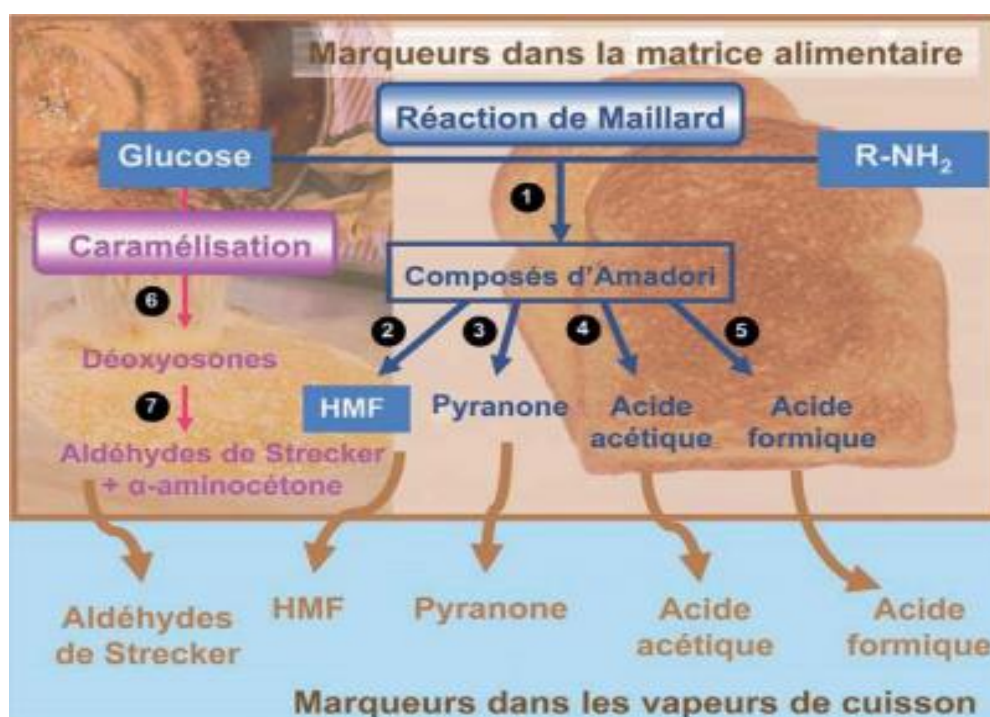


Figure 7 : During cooking, the Maillard reaction (or caramelization) can be monitored by analyzing the molecules that escape into the atmosphere (**Bonnazi, 2010**).

III.3.6.2. Influence of temperature on the reactions involved

It has been observed that the way in which the transformation is carried out has a considerable influence on the concentrations of the molecules. It is therefore possible to adjust various cooking parameters to influence the formation of molecules and thus the food itself.

Let's take the temperature parameter and set the oven to 170°C. Analyses of the quantity of molecules produced during cooking (peak area) show that they are not all generated at the same reaction rate (**Figure 8**).

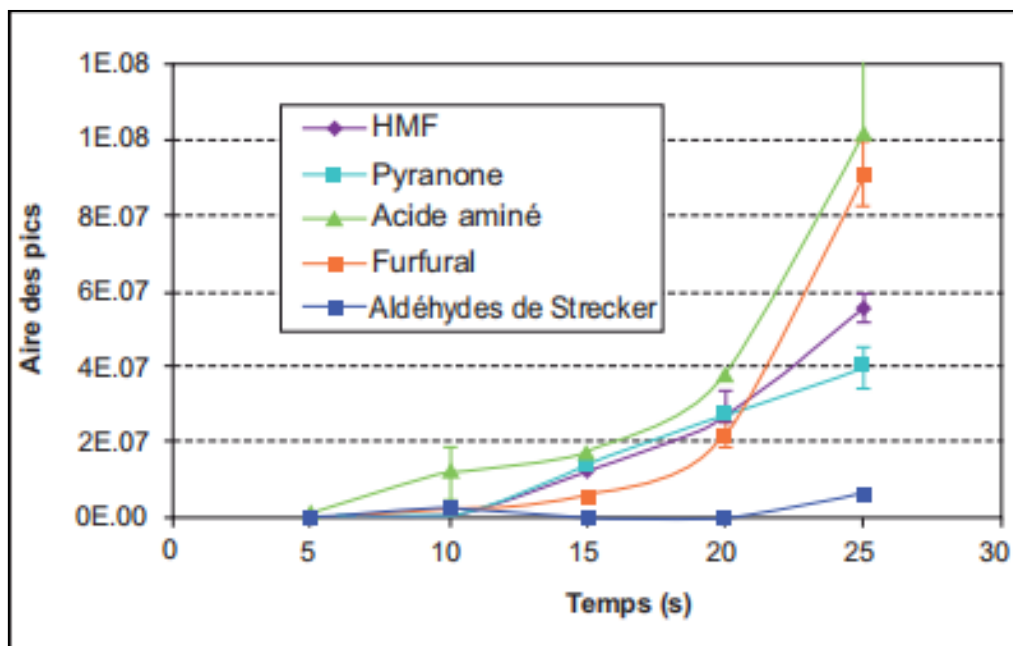


Figure 8 : Monitoring the evolution of markers of reactions occurring during the baking of a cereal biscuit at 170°C (**Bonnazi, 2010**).

Let's take a look at the HMF molecule (or 5-hydroxymethyl-2-furfural, a derivative of sugar dehydration). By tracking the quantity of this molecule present as a function of temperature, we see that at 200°C, seven times more is produced than at 170°C and 70 times more than at 140°C (**Figure 9**). It is clear that the cooking temperature has a significant influence on the reactions involved and on the nature and quantity of the resulting molecules.

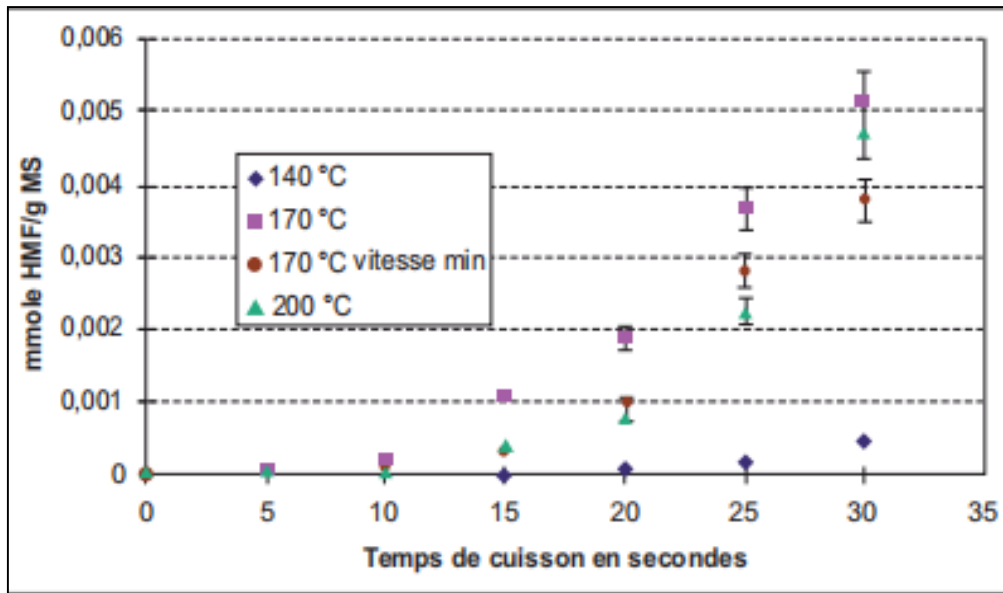


Figure 9 : The higher the oven temperature, the greater the production of HMF, which shows that increasing the temperature promotes the Maillard reaction (**Bonnazi, 2010**).

It is therefore important to control this temperature and to know the potential toxicity of the newly formed molecules (the neo-formed) in order to prevent health risks. Finally, the food matrix, that is, the chemical and physical environment of the different components in the food, also influences how reactions such as the Maillard reaction occur, as well as how molecules are transported within the food. This notably influences sensory perception (for example, flavor).

Today, many processes aim to modify the compositions of foods by, for example, reducing the concentration of sugar or fat (so-called "light" products), with the goal of improving nutritional characteristics while preserving sensory properties. We can therefore, thru composition, configure sensory perception, and, thru modification of the formulation and process, improve nutritional properties. For the food industry to be able to control the quality of food production, whether in terms of nutritional quality, health, or sensory perception (which will attract the consumer), it must understand and master the numerous parameters that influence the different stages of processing: chemical composition, physical properties, etc.

As evidenced by the example of the Maillard reaction that commonly occurs during simple cooking, and which is itself very complex to control. It is only thru understanding all these mechanisms that we can truly be active in the construction of the final product.

III.4. Formulation tools

III.4.1. Experimental design

The food industry, facing the improvement or creation of a new product, has given significant importance to the organization of experimental trials in recent years. The traditional step-by-step approach was based on the expertise and common sense of the experimenter. This resulted in numerous trials and considerable time, sometimes leading to difficult-to-interpret results.

There are three main classes of mathematical models : theoretical or deductive, empirical or inductive, and semi-empirical. Whereas the essence of theoretical modelling is the conversion of theories and concepts into mathematical formulations, the basis of inductive modelling is the extraction of information from the measured data. In this case, experimental data is the only information available and there is no need for consistent knowledge of the process mechanisms. In general, inductive modelling requires the application of statistical techniques to a data set, which means finding the best representation of the data behaviour by examining various relationships between these and potential models. Importantly, adjusting a model does not imply adjusting the data to the phenomenon.

Mathematical modelling has several objectives, such as :

- Forecast and prediction ;
- Scenario analysis (what-if) ;
- Sensitivity analysis ;
- Optimization/control ;
- Metamodelling.

Most commonly, however, the ultimate objective of mathematical modelling is to predict possible outcomes (dependent variables) from a set of inputs (independent variables). In the context of food formulation design, this is equivalent to finding the effect of ingredients and their amount/rate in a formulation on the final product's technological and sensory properties and accordingly, consumer acceptance. The impact of process conditions can also be regarded as independent variables. In practise, many models are combinations of empirical and phenomenological approaches.

Most models in food formulation are either empirical or semi-empirical, such as regression models in mixture problems, linear and logistic correlations between sensory acceptability and trained sensory panel scores, and artificial intelligence network-built models in ingredient functionality determination.

To obtain a good-quality inductive model, the model's hypotheses should reflect reasonably the behaviour of the data set, the data collection should cover the region of interest uniformly, contemplate a reasonable number of replicates, and avoid systematic error. Being data-driven, the representation and prediction power of inductive models is directly dependent on the quality of the experimental data. Therefore, well-designed experiments are the base of good empirical models.

However, the client's demands in terms of quality and taste on one hand, and the companies' race toward development cost reductions on the other hand, require the use of a scientifically rigorous approach : an "experimental design" also called an "experimental strategy."

Experimental design or design of experiments (DOE) refers to the design of experimental tests to investigate the effect of input variables (e.g. process conditions, product composition) on output variables or responses (e.g. liking scores, quality characteristics, processing time). When it comes to the design and optimization of a mixture of ingredients to meet certain technological and quality characteristics, statistical tools such as full factorial, fractional factorial, and mixture designs (e.g. simplex-lattice, simplex-centroid, D-optimal, and crossed mixture) are traditionally used. The concept of food combinatoric principles (FCP) have been introduced by **Musina et al. (2017)**, a technique to optimize the composition of food mixtures.

What are the components to study that are suspected of being able to change the result to achieve the blend that meets the expected characteristics of the product?- Thus, a chocolate industry, for example, must create several mixtures by varying the components or simply by varying their dosage to obtain a product that meets certain required organoleptic characteristics such as: melting, fatty, sweet flavor, caramelized, milky, taste persistence, colors, etc. The questions that the project manager asks themselves can be summarized in three relevant questions :

- What are the proportions of these components to put in this mixture ?

- How many trials need to be conducted to get the expected answer ?

The objective of the experimental design is to answer these questions by proposing mathematical methods that allow for the organization of a reduced number of experimental trials whose results are usable. Design of Experiments (DOE) is used in food formulation to optimize recipes by minimizing the number of trials, reducing costs, and accelerating product development. They allow for understanding the impact of several variables (ingredients, process) on the product's properties (texture, taste, stability) thru a scientific and systematic approach, often with mixture designs and response surface designs.

III.4.2. Main uses

III.4.2.1. Optimization of formulations

To determine the optimal proportions of ingredients in order to achieve specific objectives, such as a particular texture, taste, or nutritional value.

III.4.2.2. Modeling and prediction

To create mathematical models that predict the performance of a product for different combinations of factors. This allows for the prediction of the product's behavior under various conditions.

III.4.2.3. Identification of critical factors

To isolate and understand the influence of the most important factors on the characteristics of the final product, and to identify hidden interactions between variables.

III.4.2.4. Reduction in the number of trials

Instead of testing all possible combinations, experimental designs allow for a reduced number of trials to obtain complete and reliable information, which is particularly useful when trials are costly or time-consuming.

III.4.3. Examples of applications

III.4.3.1. Mixture design

To formulate products like cookies, where the mixture of ingredients must adhere to proportion constraints (for example, the sum of the percentages of ingredients must equal 100%).

III.4.3.2. Factorial and response surface design

To study the effect of process variables such as baking temperature and time on the texture, color, or yield of a product.

III.4.3.3. Sensory analysis

Experimental design can be coupled with sensory analyzes to better correlate the proportions of ingredients with the sensory perception of the product.

III.5. Marketing

In recent decades, the socioeconomic environment has dramatically changed the trends in consumption. For instance, urban consumers are progressively consuming packaged, processed, and healthy foods. This shift has moved forward for initiating market segmentation, targeted innovation, technology integration, and product preferences among consumers. The transformation of the socioeconomic landscape has also presented challenges related to aligning product quality and marketing innovations with the purchasing capabilities of varied customers. Thus, food and beverage companies rethink their marketing strategies and adopt newer practices of managing customer trends nationwide.

Consumer demand for foods with benefits beyond basic nutrition has created a category of functional foods containing bioactive ingredients becoming more prominent in the marketplace. This growing market is one of the most promising in recent times ; however, there is a need for ‘evidence-based’ functional foods. Research on bioactives currently forms a significant portion of the project portfolios of governments, universities, and food manufacturers. This work will continue to uncover novel bioactive components, developing suitable technologies for their isolation and extraction. However, reliable, science-based information is lacking for the health benefits of bioactive foods and constituents. Therefore, screening methods need to be developed for the measurement of the long-term beneficial effects, *in vivo*, in order to confirm indisputably that they can promote good health.

Furthermore, international food brands are forcing local businesses to overcome capital shortages, infrastructural issues, and regulatory inefficiencies. Thus, ensuring competitive advantage requires marketing innovation, including digital platforms, data-driven approaches, and creative branding. Ecommerce, mobile payment systems, and social media have opened new marketing opportunities. Enterprises have used these technological breakthroughs to emphasize the need for strategic excellence in connecting technology with business goals. The

food industry has been a significant contributor to the economy of countries and their culture. Hence, the food business must adopt innovation-driven tactics to be competitive in a changing market. Food sector management shapes market dynamics, with food safety, quality, and import-export laws affecting operational decisions and market access. In addition, urbanization, increased prosperity, and global influences are changing consumer behavior, leading to the need for novel marketing strategies to meet various customer requirements.

Conclusion

Different ingredients present in food systems interact with each other and in formulations based on their affinity or aversion with other ingredients present in the system. These interactions result in formation of complexes with varying physicochemical and functional properties. The macromolecular interactions are attributed to electrostatic, covalent bonding, van der Waals' force of attraction, adsorption, and others. These highly-structured composite complexes have the ability to exhibit versatile and better functional properties like hydration, solubility, rheological, interfacial, and adsorption properties, than proteins lipids and polysaccharides alone. These complexes can be used practically in foods, especially in cereal, meat, and dairy products, and as potential food ingredients such as fat replacers, texturising agents, and stabilizers of dispersed systems.

As food formulation design covers a wide range of stages, from experimental design to consumer studies to the assessment of nutrient bioavailability, it can involve a variety of different mathematical tools. This very nature of food formulation renders it difficult – if not impossible – to establish what are the best performing modelling techniques in this field. Ultimately, the choice of mathematical methods in food formulation design depends not only on the type of problem under analysis but also on the quality and size of the data set.

Chapter IV. Food life cycle

Introduction

The production and consumption of food is one of the major determinants of environmental degradation at the global scale. Likewise, individual dietary choices determine serious impacts on human health, due to an ever-growing demand for highly processed foods, refined sugars, refined fats, oils, and meats.

Unless radical changes are implemented on the production and consumption sides, global trends of population growth, increased affluence, and dietary choices are likely to worsen the impacts of food systems. The resource requirements and emissions vary widely among foods, food production systems, and regions, thus requiring assessment methods that take into account such diversity.

Life cycle assessment (LCA) is the method typically recommended by international institutions, such as the European Commission and the United Nations Environment Programme, to support policy making for sustainability by quantitatively assessing the environmental impacts during the entire life cycle of a product. Practitioners regularly use LCA studies in corporations, as well as to support eco-labeling schemes and environmental product declarations. LCA allows minimizing trade-offs between comparable alternatives, while avoiding the shifting of environmental burdens spatially from one stage or process of the life cycle to another, and physically from one environmental impact to another.

IV.1. Stages of the life cycle

The life cycle of a product takes into account all the activities involved in the manufacturing, use, transportation, and disposal of that product (**Figure 10**). The life cycle is generally illustrated as a series of stages, from production to final disposal.

IV.1.1. Extraction of raw materials

The raw materials that make up the products are often a major source of the product's environmental impacts throughout its life cycle, especially for those that do not require energy or non-energy consumption during their use and have a long lifespan.

IV.1.2. Manufacturing

The manufacturing stage of products, due to its energy and non-energy consumption, its emissions into the environment, and its waste production (packaging, products, etc.), can be a major source of environmental impacts for some products.

IV.1.3. Transport and distribution

The transportation of goods is a major source of pollution, particularly of greenhouse gas emissions. They can thus represent a significant portion of the environmental impacts of heavy products whose packaging does not allow for optimal filling of delivery trucks.

IV.1.4. Use or usage

The use of certain products involves consumption of energy, water, or other types of consumables (paper, ink, etc.). For these, the usage phase can be a major source of environmental impacts in the product lifecycle; an ecodesign approach will therefore prioritize reducing the environmental impacts of this stage.

IV.1.5. End of life

For all products, and especially those with a short lifespan, the end of life is a source of significant environmental impacts throughout the entire life cycle. It is therefore a particularly high-priority eco-design approach for these.

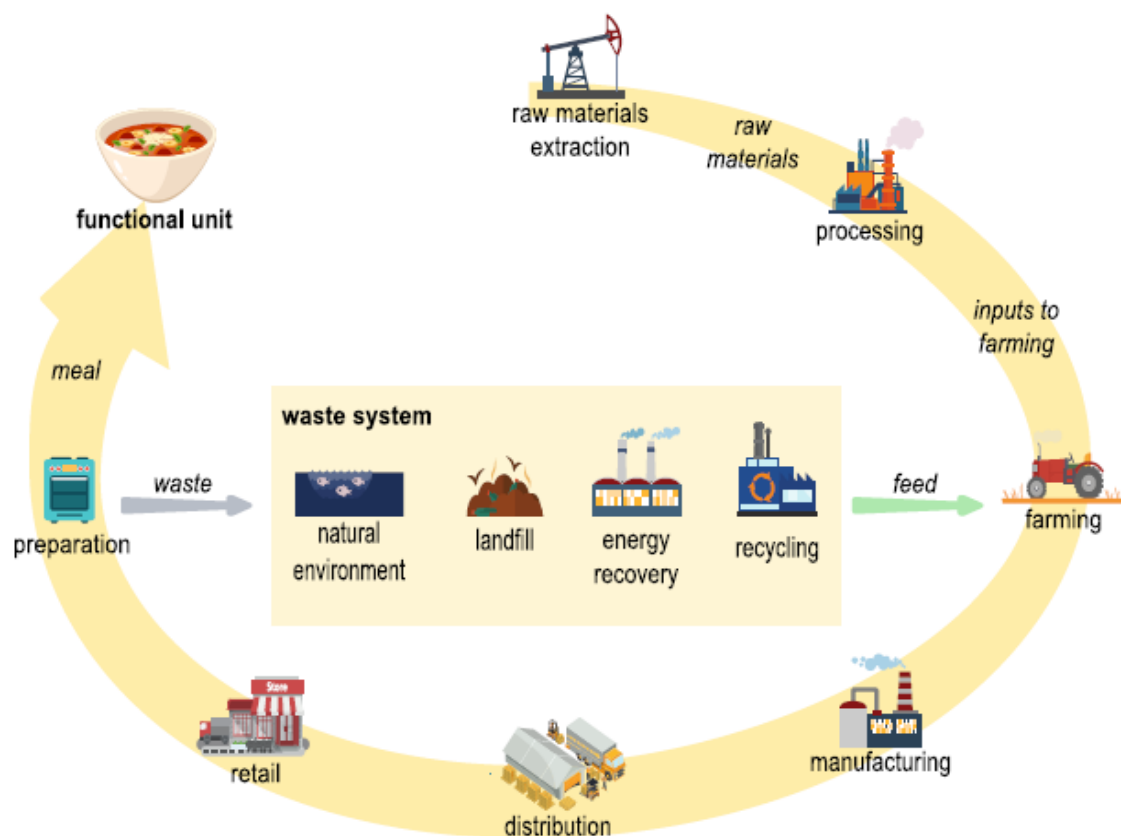


Figure 10 : The Life Cycle of a Meal (Cucurachi et al., 2019).

In order to communicate to the consumer information reflecting the main environmental impacts of products, **environmental labeling** relies on a key method for all the work : **life cycle analysis (LCA)**.

Life cycle analysis (LCA) is based on the notion of sustainable development by providing an effective and systematic means to evaluate the environmental impacts of a product, service, or process. This assessment allows for the identification and evaluation of all potential impacts of a product on the environment at each stage of its life cycle: the production or extraction of raw materials, the manufacturing of the product, its distribution, the use of the product, and the impacts related to its treatment or disposal at the end of its life.

The LCA method is a powerful tool, but its results must be interpreted with caution, as data collection is a major source of uncertainties. A binary classification of data between "good" and "bad" values, without giving the inaccuracies, makes the results less reliable. Therefore, data collection should allow for error ranges to be proposed for LCA results, which can then be indicated to the consumer.

It is difficult to convey to the consumer a system that certifies the traceability of the environmental impacts of a product like palm oil. LCA is essential, but interpreting the results can be complex, especially for the consumer. Moreover, palm oil is found in many finished products and in small quantities, which complicates traceability and consequently environmental labeling.

IV.1.6. Example: A unique score tested in large-scale distribution

Since 2011, Bio Intelligence Service, an environmental consulting firm, has developed a labeling methodology for Casino communicated in the form of a single score, the result of which is the environmental index.

Three indicators were evaluated : greenhouse gas emissions, water consumption, and eutrophication.

By aggregating the results of the LCAs, the single figure obtained represents the environmental impact of 100 grams of product compared to the total impact of a French person's daily food consumption.

" This index provides a reference point for the consumer, just like nutritional information".



IV.2. Innovation acclaimed by consumers

Manufacturers are constantly introducing new products to the market to stimulate consumption, which is particularly sensitive to innovations.

The consumer appreciates novelty presentations, new associations are mainly offered to young adults and obviously to children. The consumption of cheeses, for example, is constantly revitalized by the introduction of new varieties to the market.

Let's take ice cream, for example, which has become a market in just a few years whose health depends, in addition to climatic uncertainties and advertising investments, more and more on innovations and their potential to attract consumers. It is clearly the novel products that are recruiting, by creating new moments of consumption.

IV.3. Organic : a return to authenticity that reassures

IV.3.1. A massive rejection of Genetically Modified Organisms (GMOs)

According to a French survey, 71% of consumers do not want to buy transgenic foods (GMOs), with the majority thinking that they can be dangerous to health. 36% think that the popularity of organic products corresponds to a sustainable evolution, like a safe haven, in the face of concerns about mad cow disease, etc.

IV.3.2. The "boom" of "Organic" products

"Organic" products, or more precisely those derived from organic agriculture, are gaining momentum. Indeed, they enjoy a strong capital of sympathy from both consumers and distributors.

Indeed, it turns out that consumers expect a health benefit from organic products, that is to say, a promise that is very difficult to keep. Certainly, foodstuffs are grown without synthetic chemicals, but surrounding crops can bring traces of these products, and zero pesticide content is difficult to achieve. The second argument put forward by consumers is that "organic" products taste better. However, this criterion, due to its subjectivity, is difficult to measure.

IV.3.3. Return to "more natural" products

Consumers are becoming increasingly attentive to what they buy and what they consume. The certification of origin is a guaranty of quality and reassures the consumer, who is gradually becoming more educated. There is therefore a real demand for the origin of products and their taste.

Faced with the globalization of trade and the standardization of industrial products, consumers are trying to find a human dimension in the product.

Conclusion

The production and consumption of food are responsible for serious environmental degradation. Given the nature of the global economy, the impacts of food are dispersed over the full extent of the planet because food commodities may travel long distances from production to consumption. In this Primer, we introduce the principles of life cycle assessment (LCA), which allows for the assessment of the global extent of the inputs, outputs, and potential environmental impacts throughout the life cycle of a product system.

While LCA has been expanding in scope and breadth, collaboration across disciplines is needed to further capture the diversity of food systems and to better deal with underassessed foods.

Chapter V. Innovation for the formulation of natural foods

Introduction

In an era where awareness of the importance of health is on the rise, the quest for consuming natural foods has become much more than just a trend ; it's a lifestyle choice for many. In recent years, consumers have increasingly sought out foods that are not only nutritious but also perceived as "natural." This change in preference has triggered a wave of research on what constitutes naturalness in food, how it affects consumer choices, and the impact of food processing technologies on perceived naturalness and the nutritional value of food products. The food processing industries must shift their processes toward healthier choices and the use of innovative processing technologies. However, it can be complex to correctly perceive this notion of naturalness for the end consumer.

This chapter is based on a series of targeted scientific publications that address:

- The notion of consumers' perception of the naturalness of food products;
- A tool for measuring naturalness: the Food Naturalness Index (FNI)
- Recent innovation pathways opening new perspectives: new colorants, natural preservatives and functional ingredients, and new physical transformation technologies.

V.1. Understanding consumer preferences: what is naturalness?

Naturalness is a complex and abstract concept with multiple dimensions. Its interpretation often depends on the perspective being considered-whether technical, legal, or consumer-driven. Food naturalness is typically characterized by the absence of “negative” attributes, such as additives, pollutants, or extensive human intervention, rather than the presence of inherently “positive” traits.

The factors influencing consumers' perceptions of naturalness categorized into three categories:

- the way the food has been grown,
- how the food has been produced, and
- the properties of the final product.

The review also emphasizes that most consumers consider the products' naturalness as a key factor in their purchase decision. Accordingly, recent evidence shows a significant global

increase in the number of food and beverage products labeled with claims such as “natural”, “all-natural”, “100 % natural” and “100% natural ingredients”.

Battachi (2020) provides some guidelines for targeting the more or less consensual factors according to scientific reviews and official government recommendations: raw material (natural vs artificial), processing, agricultural practices (organic farming vs pesticides/Genetically Modified Organisms), and the environmental impact of the food's life cycle. Moreover, **Espinosa-Brisset et al. (2023)** concluded that the method of processing (industrial vs homemade) of fruits seems to have more impact on consumer preferences than the farming method (conventional agriculture vs organic agriculture).

V.2. Choice of ingredients : key to the quest for naturalness in food

The ingredients used play a crucial role in perceived naturalness. The development of the Food Naturalness Index (FNI) is a significant step toward quantifying the degree of naturalness based on agricultural practices, the absence of additives, and the level of processing. This tool can guide food manufacturers in reformulating products to meet consumer demand for more transparency while providing a basis for regulating claims of the term "natural" in food marketing. It was demonstrated that the FNI score based on label data is well correlated with consumers' perception of naturalness.

In light of this regulatory ambiguity, in 2017 the **International Organization for Standardization (ISO)** issued **ISO/TS 19657: 2017**, establishing technical criteria for classifying food ingredients as “natural”. While the standard provides definitions and evaluation guidelines, it is intended primarily for business-to-business (B2B) communication. Therefore, it does not offer a universally recognized definition of “natural” suitable for food labeling aimed at consumers. As a result, the absence of a binding standard for consumer communication leaves considerable room for interpretation and leads to inconsistencies in how the different “natural” claims are applied across products.

This regulatory gap may lead to a discrepancy between consumers' expectations of products labeled as “natural” and the actual characteristics of those products. While other food labels like “organic” are governed by strict regulations and have been extensively studied for their impact on consumer perceptions, research on “natural” labeling remains comparatively limited. These limited studies indicate that products labeled as “natural” are perceived as healthier than identical products without the label, leading to a higher likelihood of purchase and a greater willingness to pay a premium price. However, most of these studies have

focused on a single food item (e.g., yogurt, pork, beef, peanut butter, or sugary fruit drinks), which limits the generalizability of their findings. In the absence of specific regulation, natural-related labels become a powerful yet loosely defined marketing tool, enabling marketers to boost their sales without meeting rigorous standards as required for other food labels (e.g., organic). As recently noted, this unregulated use of natural-related claims has the potential to mislead consumers and calls for consistency in marketing campaigns.

V.3. New perspectives for innovation to accelerate naturalness in the food industry

V.3.1. Choosing effective natural colorants

Natural food is healthy and becomes a trend due to the availability of many nutrients. Nowadays people are concerned about a healthy diet and natural additive addition is demanded. Most food products are thermally processed, and sensory attributes such as color and flavor are affected so the food additive addition is compulsory to improve the product properties. Food color is an important characteristic not only to look food fresh but also to appeal to the consumers. Artificial pigment applications are limited due to the main reason for many chronic diseases. Natural pigments application is demanded due to its presence to health benefits and fewer toxicity concerns. However, some limitations and challenges are also associated with natural pigment application such as cost, efficiency, and stability. Only approved pigments by U.S. Food and Drug Administration (FDA) under regulations are applied in food products. Sufficient knowledge about the pigment's source would be helpful in better applications of these pigments in food industry.

V.3.2. Investigate the applicative potential of natural preservatives and functional ingredients

The trend toward naturalness extends to food preservatives and functional ingredients. Natural preservatives derived from plant materials and functional ingredients like plant protein isolates as emulsifiers are gaining attention. These natural alternatives not only improve the safety and shelf life of food products but also offer health benefits.

V.3.3. Define the balance between food safety and functionality and naturalness thru new processing technologies

The application of new preservation technologies allows for a reduction in the use of preservatives. Indeed, some emerging processing technologies such as high-pressure processing (HPP) offer the promise of safer foods with an extended shelf life without compromising their naturalness attribute. These technologies are perceived as

environmentally friendly and capable of producing more natural foods. These include, for example, technologies that implement physical principles (reduction in ingredient size, use of pulsed electric fields, irradiation, etc.).

It is interesting to note that in the case of dairy products, the transformation of the food seems more accepted as natural than for other categories of food. However, consumers can quickly associate the notions of "Ultra-processed" and "Addition of artificial ingredients," which is detrimental to the development of innovative processes. Chemical processes, on the other hand, are the most poorly perceived.

V.4. Perception of the naturalness of industrial foods: what prospects?

Consumers place a high value on processing techniques when judging food naturalness. Foods produced using traditional methods or inputs are perceived as better than those produced by industrial processes or using modern, non-indigenous inputs, and modern versions of traditional foods can be perceived as less traditional, and less natural. Seemingly, information evoking a traditional process can have an influence on consumers' expectations and hedonic judgements of food products. Industrially-produced foods, on the other hand, are expected to be less tasty, less flavourful, and have a less pleasing appearance, than foods prepared using traditional methods.

Industrial processing is associated with diminished naturalness due to limited human contact, the use of machinery and automation, and a focus on efficiency (of inputs and time), rather than quality of the final product. As such, processing tends to reduce perceived naturalness of food. Further, the more processing steps a food item undergoes, the less natural it is perceived to be, regardless of whether the processing resulted in a nature-identical, or healthier product. Processing also seems to destroy naturalness more when it involves addition, than subtraction (additivity dominance), so that milk with added vitamins is seen as less natural than skimmed milk.

The exploration of understanding and improving the naturalness of our diet is ongoing. Future research should delve deeper into the themes of consumers' perception of naturalness and the impact of non-thermal processing technologies on food safety and sensory properties. The development of natural alternatives for additives and colorings also helps to meet consumer expectations. The food industry must choose to prioritize transparency and communication to align with consumer values and ensure the success of natural food products.

Conclusion

Consumers increasingly seek foods perceived as natural, wholesome, and minimally processed. The association between naturalness and perceived safety or health benefits remains strong, even in the absence of full scientific consensus, and it significantly influences both ingredient selection and purchase behavior.

This health-conscious orientation is reflected in several observable trends. Consumers tend to avoid artificial chemicals, synthetic additives, and overly processed ingredients while showing a marked preference for familiar, plant-based components such as fruits, vegetables, whole grains, and legumes, which enhance recognizability and trust. Additionally, there is growing demand for bioactive-enriched functional foods, including antioxidants, fibers, and probiotics, aimed at supporting digestive, immune, or cardiovascular health.

These consumer expectations have important implications for formulation and processing. Manufacturers are increasingly reformulating products to align with health-focused trends, prioritizing ingredient transparency, nutrient density, and minimally processed alternatives to synthetic components. Cultural and personal beliefs, regional traditions, and digital communication channels, including social media, further amplify expectations for naturalness, influencing sensory attributes, labeling approaches, and marketing strategies.

Chapter VI. Artificial Intelligence (AI) in New Product Development

Introduction

Analyzing customer needs is a particularly difficult process that involves a tedious management process between customers, marketers, and designers. The development of products and services with high perceived quality and customer involvement in co-design is no longer an option for the company. This involves working closely with customers to help them develop a more precise understanding of their needs, which is not always trivial. Moreover, it is a process with inherent difficulties of semantics and terminology. This leads to the adoption of methods and technologies that can make the exchange smooth and can handle the lack of coherence and cohesion in communication and information exchange.

Over the past decade, AI-based approaches have been widely used in various fields to solve complex problems. Similarly, the adoption of AI has demonstrated its potential in personalized product design and customer management. Advanced AI offers great potential to improve the needs management process.

In this context, this work provides an overview of the research and advancements in the adoption of AI to analyze customer needs, in order to understand the multiple dimensions of AI's key capabilities, its challenges, its limitations, and its orientations in customer needs management.

VI.1. Concept

"The main objective will always be to meet the client's challenge, AI is just one of the tools to achieve this."

AI promises to transform food production sites into smart factories, adopting a highly responsive, adaptive, and connected manufacturing model. Smart factories offer many cost-saving benefits, including better resource utilization thru improved connectivity, predictive maintenance, and condition monitoring; online quality inspection, automation of manual operations, learning autonomous systems, and adaptation to changing situations. As you may have guessed, not all of these improvements come from AI. Rather, it is a component in a revolutionary suite of Industry 4.0 technologies. The ultimate goal is intelligent automation, a comprehensive approach that integrates human workers, robotics, process automation systems, and AI.

VI.2. Challenge of simplicity

As AI techniques become increasingly sophisticated, new challenges arise regarding the accuracy and explainability of the technology. Because machines perceive data in a fundamentally different way than the human brain, almost no one, aside from the most highly trained data scientists, can interpret the logic behind AI decisions.

This situation is problematic for the food and beverage industries where decision-makers need to ensure that the company operates efficiently, ethically, and that their AI recommendations are reliable. To address this, Microsoft has come up with a new technique: "Machine Teaching." Specialized workers use their expertise to literally teach machines to make better, easier-to-understand decisions by showing them how to break down problems into simple steps. They then guide the machine to solve complex tasks more quickly by using a "lesson plan" that explains important information and gives advice on how to self-measure the effectiveness of a measure. By teaching machines how to structure their calculation methods by drawing inspiration from human thought, it becomes easier to understand the reasons behind their recommendations. This speaks to the enormous potential of digitization to capture and retain the expertise of skilled veterans that otherwise disappears with them when they retire.

VI.3. Food, inverse design, AI and generative models

The ultimate goal of developing and discovering new products is to meet requirements related to cost, time, quality, safety, shelf-life, and consumer needs. Therefore, a similar design and discovery methodology can be applied across various products, including food products. However, the design and discovery process is complex due to the large number of factors affecting the achievement of optimal design (or solution) while fulfilling target requirements. These factors are referred to as design variables in the development and discovery process.

The conventional approaches for designing and discovering food products are based on rational design frameworks that utilize trial-and-error methodologies. As a result, these approaches are often expensive in terms of both time and cost. The rational design framework for food products involves several sequential stages, as demonstrated in **Figure 11** (top). First, a food idea is identified, and then conceptualization follows to define the criteria for an optimal product. This is followed by idea screening, design specifications, and development and optimization. Because of the iterative nature of this approach, any failure at a stage can set the design process back to the previous stages, resulting in undefined iterations until the

desired product functionalities are achieved. Sometimes, luck can also play a role in the discovery and design process, particularly in approaches where initializing the design process is critical to reaching optimal solutions. Moreover, the cultures of both designers and consumers are factors that can significantly affect and limit the process of discovering new food formulas and products.

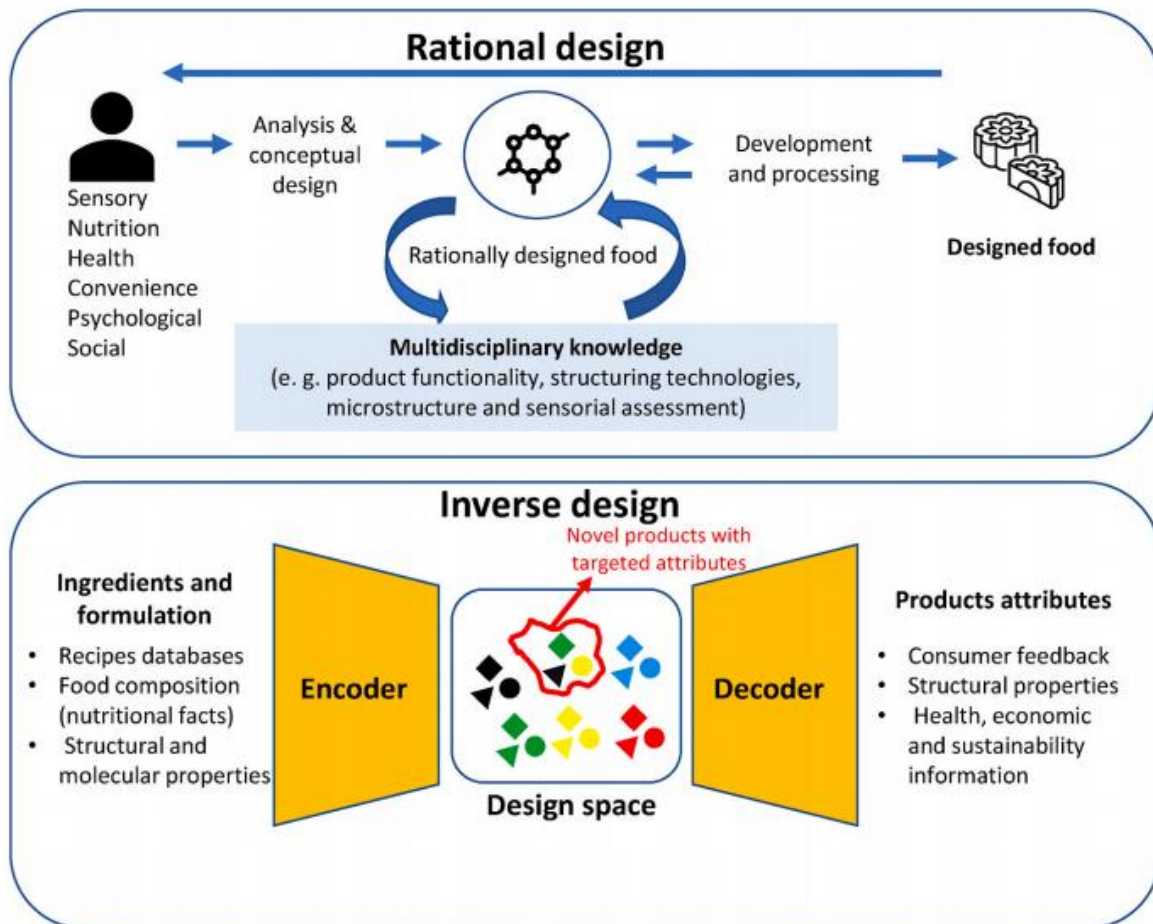


Figure 11 : Illustration of the rational design and inverse design frameworks for food design and formulation (Al-Sarayreh et al., 2023).

Recently, inverse design frameworks have been developed with the aim of reversing the conventional design process paradigm. These frameworks begin by identifying the desired functionalities of the product to be designed (inputs of inverse design framework) and end with an optimal design that maximizes the desired functionalities of the newly designed product (outputs of the inverse design framework). This concept requires robust modelling strategies to understand the complex relationships between the inputs and outputs of the design process. Due to the large number of design variables involved, these modelling

strategies are often beyond human capacity. Compared to the rational design framework, the inverse design framework can provide a better understanding of the design space and support decision-making mechanisms. It also permits incorporation of experts' knowledge to guide the process towards the optimal design, especially if the number of design parameters is very large. **Figure 11** illustrates the differences between the rational design methodology and the inverse design framework from the food design and formulation perspective.

AI-based approaches, such as machine and deep learning algorithms, are robust tools for understanding the complex patterns and relationships between inputs and outputs in any design process, provided that the necessary data is available. These algorithms can be used to support the inverse design methodology for product design and discovery. The inverse design framework, combined with deep learning algorithms, can be simplified into two main components, as demonstrated in **Figure 11** (bottom) : the encoder and decoder components. The encoder translates inputs into a numerical representation. For example, a recipe of a cake including text with ingredients, instruction and quantities is translated into a numerical representation. A set of these numerical representations form a 'design space' (for example the design space of a cake, including the numerical representation of thousands of cake recipes). The decoder translates that numerical representation into a format similar to the input, for example, a recipe. The key idea is to develop (or train) both the encoder and decoder simultaneously in such a way that the new space can be used as a design space representing design variables. This can be used to discover optimal or novel inputs to be used as candidates for manufacturing or fabrication.

VI.4. AI approaches for food design

AI approaches, such as machine and deep learning algorithms, are data-driven models that can be used to extract and learn hidden patterns and relationships between inputs and outputs for prediction or data representation. Thus, these approaches can be used to learn, generate and better understand the design space, of product to be designed, aiming to automate and accelerate the design and discovery process of products. Recently, novel design methodologies, based on machine learning and deep learning, are proposed as a robust technology supporting inverse engineering methodology for materials design and discovery.

VI.4.1. Inverse design

The inverse design approach begins by identifying the desired functionalities of a product and aims to create an optimal design that maximizes these functionalities. To achieve this, robust

modeling strategies are necessary to learn, extract and understand the complex relationships between inputs and outputs of the design and discovery process of products. Machine learning and deep learning provide the capability to describe those complex relationships between a large set of input attributes and link them with the measured outputs. Thus, machine learning and deep learning are required tools for developing inverse design frameworks for designing and discovering any type of product including food or materials.

In the last 10 years, inverse design based on AI algorithms (i.e., machine learning and deep learning models) has received attention in many domains in the field of matter engineering including food design related to food pairing and recommendation. These approaches allow the machine to connect the chemical, physical, and physicochemical properties of materials by utilizing existing resources such as public and commercial databases and simulated data that can be generated by the material design tools.

Learning-based models are used to estimate the distribution of the design space (also called latent space) of the design variables and conditions that can be used for generating new samples as a new design to be investigated. Then, to achieve the inverse design property, optimization, sampling, and search methods are used to navigate and reshape the estimated distribution toward maximizing the desired functionalities of new designs. Therefore, the inverse design offers promising potential for food design based on AI, especially when comes to the design of complex characteristics such as food functionality. The following sections then revise key approaches to inverse design that are relevant to food design.

VI.4.2. Data representation methods

In inverse design frameworks, the representation of the inputs and outputs is very important and one of the key challenges for developing successful applications. Inputs and outputs can be any information related to the product or material to be designed, for example, chemical formula, measured properties, or textual data describing a specific process. The representation should be an informative representation that can be used to describe the target formula of a material as well as calculate its physical and chemical properties. For inverse design, the most desired property of the representation is the invertibility to allow the designers to map back the optimized formula into a characterized material.

The current representation of materials can be categorized into graphs (e.g., weighted, directed, and undirected), discrete (e.g., textual data), and continuous representations (e.g., vectors, matrices, and tensors). The continuous representation is a general representation used

to describe design variables and as inputs and outputs for an AI algorithm. It can be a vector of N elements to define the design variables, matrices such as image-like data that can be used to represent the structure of chemical species, or tensors to represent the data in higher dimensional space (such as 3D geometry). 2D or 3D data representation can be advantageous for capturing spatial relationships between the inputs by using advanced AI modeling approaches such as convolutional neural networks (CNNs) models. However, the invertibility property is a challenge in this type of representation. For food products, the design and formulation processes involve several layers of complexity (e.g. phenomenological models, assessment of food attributes, consumer acceptance) and the necessary data is not always easy to be obtained. A data-driven approach can be used to overcome the challenge of collecting a large amount of data to satisfy one of the requirements (i.e., the size of the dataset) of AI-based approaches. There are many resources related to food design that is publicly available and can be automatically accessed.

Food recipes is publicly available resources providing rich sources of information for development of AI-based frameworks for food design. The information in a food recipe (as illustrated in **Figure 12**, can include :

- Visual properties of the final product (e.g. photo of the dish);
- ingredients (including quantities and units);
- the flow of operations as an ordered set of instructions (including processes and dependencies among ingredients);
- nutrition facts; and
- consumer preferences and functional properties (e.g. product texture) present in consumer feedback and comments.

Publicly available resources are unstructured data requiring processing so that can be utilized in an AI-based design framework. For example, consumer comments are a very important piece of information to estimate the functional properties of products such as flavour and textural properties. This textual information requires special pre-processing to be informative and valid for any AI-based design framework. For example, the sentence ‘This chocolate cake is not bad and the taste is rich’ is converted into a matrix, where each word is represented by a vector, for example, rich is represented by the vector [0.2, 0.3, - 0.1, ..., 0.7], in a process called word embedding.

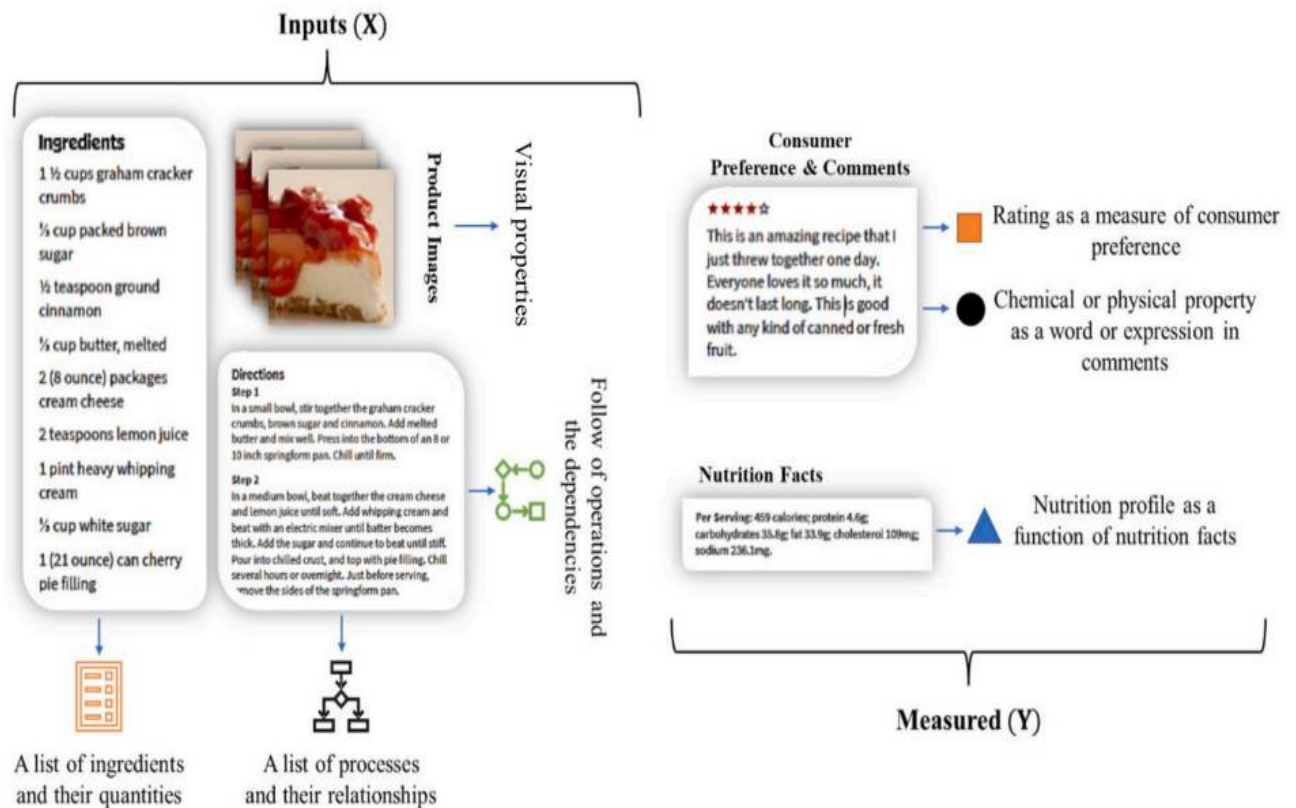


Figure 12 : Illustration of the available information in food recipes that can be utilized by AI frameworks for food design. ‘X’ represents inputs and ‘Y’ the measured attributes associated to a given input ‘X’ (Al-Sarayreh et al., 2023).

VI.4.3. Deep generative models for inverse design

The generative models aim at approximating the joint (or conditional) probability distribution of X and Y and can be used to calculate $P(x|y)$ which can be then utilized to infer the same $P(y|x)$ as in the case of discriminative models by applying the Bayes rule. In the context of food design, generative models can be used to generate new and novel food recipes, including all necessary information to prepare the food. The main advantage of the generative models is the ability to learn the true data distribution in either a supervised $P(x, y)$ or unsupervised $P(x)$ manner. The learned true data distribution can be used to sample new data samples that can be used in the discovery of the learned space.

Deep generative models are efficient to learn information about products and propose new candidates for new products, being an important tool for inverse design processes. In the current review, we focus on the following three deep generative models that are typically used in inverse design processes: autoencoders networks (AEs), generative adversarial networks (GANs), and recurrent neural networks (RNNs).

VI.5. Potential resources for the digital formulation of food products

Inverse design utilizing an AI-based approach is data-driven requiring comprehensive and representative sets of data.

The most common type of database, publicly accessible online, is a food composition database, such as FOODB which provides comprehensive information concerning the composition of the food being searched, as well as the details of the compounds and the nutrients contained. The New Zealand Food Composition Database (NZFCD), the Australia Food Composition Database (AFCD), USDA FoodData Central, the Swedish National Food Database, the Malaysian Food Composition Database (MYFCD), Dutch Food Composition Database are of the same type but based on more country-specific food composition information. These commonly used food composition databases can be limited to data obtained from chemical analyses, and nutrition estimation from the recipe, and the number of foods or components included in the database is also generally limited. Some databases provide more information than food composition data, such as INFOODS which also provides contact information and links to the regional food data center. Food databases have also been developed to serve more specific purposes, such as first foods focuses only on baby foods, with food safety, allergy advice, recipes, and recommended flavor pairings provided; FoodData Central groups their data into five types and provides food and nutrient profiles for foundation foods, dietary studies, Standard Reference Legacy Release (SR Legacy), global branded food products as well as experimental foods.

Recipe and cooking websites are another source of data that can be easily and freely accessed. These websites often provide significant information such as ingredient lists and their quantities, cooking directions, nutrition profiles, visual information like images and videos, and consumers' feedback like ratings and comments. On the other hand, social media data can be used to extract significant data about food formulation and processing conditions. For instant, cooking channels provide detailed information about food recipes as well as the response from followers. This package of information is very useful to discover new food recipes and ideas based on generative models.

VI.6. Defining AI for Business and NPD

In their book *Prediction Machines : The Simple Economics of Artificial Intelligence*, **Agrawal et al. (2018)** offer a pragmatic definition of AI as a “prediction technology that reduces the cost of predictions.” Where humans make predictions today - for example, market forecasting - AI makes them faster, better, and cheaper. For problems that do not involve prediction, AI

will take the traditional problem, such as creating the drawings for a new concept car, and turn it into a prediction model ; AI will predict how a creative artist would draw the car, given specific instructions. Prediction is at the heart of making decisions under uncertainty, which is a major part of any new product project, hence AI is already having a transformative role in NPD.

Currently, more than 40 unique AI applications exist for AI in NPD. The varied nature of the applications— everything from doing market research to undertaking engineering design iterations— is exciting and somewhat over-whelming. Where does one start ? A positioning map for “AI in NPD”- showing 40 different AI applications (apps) in NPD (but which is not an exhaustive list) - gives a visual presentation of this complex landscape (Figure 1). Its two axes answer the questions “Where ?” and “How ?” Across the map is where the AI application occurs in the NPD process from idea to launch. Along the left side of the map is the role of AI as 1) an originator, the creative and inventive side of AI, or 2) a facilitator, doing what is done now, only faster and better.

Table 4 present tools and applications that are relevant to each stage of the NPD process.

Table 4 : AI tools and applications (Cooper and McCosland, 2024).

AI Tools and Applications	
Front End	• Generate novel ideas with generative AI (e.g., ChatGPT). • Scan the Internet (unstructured text) to identify market gaps and emerging customer needs. • Define the opportunity by scanning blogs, online complaints, and user comments. • Analyze text responses from surveys and interviews. • Generate a first draft of a customer interview guide. • Generate new product concepts—AI transforms scanning insights into concept proposals. • Evaluate concepts. • Mine internal technical data (research reports) to find opportunities for exploitation of IP. • Design and draw product concepts from verbal commands. • Do iterations of concept drawings with impacts.
Business Case	• Analyze market data from online, yields insights. • Make predictions: market size, sales, pricing, and costs. • Monitor competitors' activities: launches, pricing, etc. • See technology trends and technology disruptions. • Get facts on a specific technical subject, answers on technical questions (e.g., ChatGPT). • Analyze financial data, and make revenue and profit projections. • Simulate different scenarios, gauge impact of factors like price and competition on profits. • Predict how well a particular product will sell. • Identify potential risks and propose mitigating actions.
Development and Testing	• Create 3D models and generate technical drawings. • Create mockups and virtual prototypes. • Design products with the right features and dimensions. • Design products that are more user-friendly and aesthetically pleasing. • Develop digital and virtual prototypes for rapid product testing. • Do multiple design iterations and analyses quickly. • Undertake structural optimization—reduce weight and cost. • Optimize design with digital twins, which are able to mimic a product in the field, monitor it, and collect data on its operation. • Create or discover products (chemicals, drugs). • Automate project management.
Back End	<i>Market Launch:</i> • Create the market launch plan: the strategies and tactics. • Create advertising text, images, videos. • Do lead scoring for the salesforce, also routing, even suggest best actions for the sales team. • Manage product distribution, get the right product assortment. • Optimize pricing strategy. <i>Production or Manufacturing:</i> • Optimize production processes and warehouse processes. • Use digital twins to simulate machines and factories. • Employ digital twin simulations to validate new production techniques and systems. • Manage the supply chain. • Provide employee training. • Manage quality control. • Employ blockchain to track goods in real time. <i>Post Launch:</i> • Analyze customer feedback and market data to see use patterns, user comments and complaints. • Use digital twins to monitor performance of products in use and to spot issues.

Conclusion

Artificial Intelligence (AI) has been around for several decades, quietly automating tasks and making things like data analysis more efficient. Only recently, however, has AI has begun to transform new product development (NPD). Currently, just 30 percent of new product projects succeed commercially ; AI offers tremendous potential for improving NPD results. Early-adopter firms have demonstrated that AI has many applications in the NPD process and can yield substantial pay-offs- as much as a 50 percent reduction in new product development times.

Chapitre VII. Applications of AI in sustainable food manufacturing

Introduction

The true advantage of AI is that it doesn't just automate - it optimizes. The more data it collects, the more efficient it becomes. Over time, it identifies bottlenecks, anticipates inefficiencies, and suggests process improvements.

In the food industry, quality control is crucial. A single undetected defect or safety issue can lead to significant losses, costly recalls, or even serious health risks. That is why AI is becoming an indispensable tool in modern production — bringing speed, precision, and consistency to every stage of the process. AI vision systems digitize products in real time and detect anomalies that human inspectors might miss. These systems inspect thousands of items per hour without slowing down or losing efficiency. Thanks to machine learning, the models improve over time, analyze production data, recognize trends, and adapt to seasonal variations or new product releases. In addition to detecting defects, AI enhances food safety

It's not just about avoiding incidents — but ensuring the finished product is always of the highest possible quality. For manufacturers who have to deal with regulatory compliance, high consumer expectations, and tight margins, AI-driven quality control is much more than an asset: it's a competitive advantage.

VII.1. Production optimization

AI holds immense potential to optimize production and discover ways to improve the operation of manufacturing sites in order to meet, or even exceed, key performance indicators. Examples of applications include speeding up production changeovers, reducing the time it takes to switch from one product to another, or identifying production bottlenecks before they become a problem. Today, an operator is still needed to "tweak" the recipe or process, but in the future, models will be trained to automatically calibrate production, which will improve quality and production speed.

AI systems will also soon be able to use machine learning algorithms and physical models to predict common failures and resolve them on their own. Preventive measures can also be taken during planned downtime. The ability to anticipate and avoid unplanned shutdowns minimizes the risk of production loss, costly repairs, and the need to maintain a large stock of spare parts.

Packaging is another area where AI can play a role. Faced with decreasing production batch sizes, diversifying packaging requirements, and fragmented distribution, AI can play an essential role in optimizing pallets and loads.

For example, a large dairy produces around 1.5 billion plastic yogurt pots a year, whose shape, material distribution, wall thickness, and weight were manually checked every 30 minutes. If an anomaly was detected, it had to be corrected manually and, in the worst-case scenario, everything that had been made since the last measurement also had to be removed from production. An online quality control optimized by AI and robotics helps avoid all these potential problems by eliminating manual interventions, thanks to a faster and fully automated approach.

VII.2. Food waste reduction thru predictive analytics and circular economy

Food waste is one of the industry's greatest challenges — financially, environmentally, and ethically. From unsold inventory to expired products, losses can occur at any stage. AI offers producers new ways to tackle this problem at the source.

Predictive analytics allows production to be aligned with actual demand. By analyzing a vast dataset — past sales, seasonality, weather conditions, holidays, local events — AI forecasts demand with much greater accuracy than traditional methods. This allows companies to:

- Produce just what is needed to avoid costly overproduction;
- Optimize stock levels to reduce losses;
- Adjust distribution in real-time based on demand fluctuations;
- Ensure more efficient stock rotation to avoid expired products on the shelves.

Moreover, AI helps identify where waste occurs. Vision systems can spot damaged products, overfills, or spills on the line. By tracking expiration dates and usage patterns, it also helps improve the management, rotation, and sale of ingredients and finished products. In some cases, it even facilitates redistribution — by directing surpluses to food banks, meal programs, or discount stores.

VII.3. Energy-efficient process optimization

Optimizing energy consumption is also a key element in optimizing production. AI can further improve this process at the factory level by forecasting energy needs, planning

production to minimize demand peaks, and maximizing renewable energy sources by balancing variable rates.

VII.4. Real-time food monitoring with AI : Ensuring safety and predictive maintenance

Food safety protocols do not tolerate any errors. Consumers expect the food they buy to be safe, consistent, and reliable — and regulatory bodies demand it. That's why a growing number of producers are adopting AI-driven systems capable of continuously monitoring safety conditions and responding instantly when a parameter deviates from the norm. Modern AI tools work in synergy with smart sensors to monitor essential indicators throughout the production site, including:

- temperature and humidity;
- pH and moisture content of products;
- air quality and pressure, as well as odors.

These sensors continuously transmit their data to AI systems, which analyze them instantly. If a parameter falls outside the acceptable range — for example, if a refrigeration unit starts to warm up or if the packaging pressure drops — the system doesn't just wait for an operator to notice: it immediately sends an alert, allowing action to be taken before a minor incident becomes a major safety risk.

AI also supports preventive maintenance by analyzing machine behavior to detect signs of wear or failure before they cause food contamination. Rather than reacting to a broken valve or a faulty seal, teams can intervene proactively — thus avoiding production shutdowns and health risks.

Another major advantage: **Traceability**. AI systems record everything, creating a detailed digital history of checks and interventions. In case of a problem, producers can immediately identify the cause, isolate the affected products, and provide the required documentation to comply with regulatory requirements — without having to sift thru paper files or Excel spreadsheets. Thanks to these AI-driven solutions, food safety monitoring shifts from a reactive approach to a proactive one.

VII.5. Supply chain optimization using AI

The food supply chain is a complex and constantly evolving system — and when one link breaks, the repercussions can be considerable. From weather disruptions to demand

fluctuations, transportation delays, and spoilage risks, producers are under constant pressure to stay ahead. That's where AI brings the necessary agility and precision.

AI helps companies predict demand in real-time, using both historical sales data, weather trends, and market signals. Producers can thus plan more effectively, ensuring they manufacture the right quantities and route products to where they are most needed. Beyond forecasting, AI is transforming logistics and distribution. Intelligent route optimization tools analyze traffic conditions, road conditions, and delivery slots to determine the most efficient routes for trucks and distribution fleets. This not only saves time but also reduces fuel costs, lowers emissions, and preserves the freshness of products. AI also enhances inventory management by:

- monitoring inventory levels across all facilities; predicting potential stockouts;
- suggesting optimal times for restocking;
- balancing inventory between regions to avoid surpluses or shortages.

In an industry where margins are tight and freshness is paramount, these efficiency gains are crucial. By automating and improving decision-making at every stage of the supply chain, AI enables food companies to reduce waste, quickly adapt to market fluctuations, and deliver higher-quality products — faster. And when unexpected disruptions occur, AI-driven systems help teams react quickly, by rerouting deliveries or reallocating inventory before it becomes a problem. In the current context, where the supply chain is particularly vulnerable, this adaptability is a major strategic asset.

VII.6. More informed decisions thanks to AI data

Data has always been part of food manufacturing — spreadsheets, reports, tracking charts — but today, AI is transforming it into something much more powerful : truly actionable insights. From the production workshop to the boardroom, it helps food companies make faster, more relevant, and data-driven decisions in real time.

Thanks to AI-driven analytics, teams no longer rely solely on instinct or manual reports. They now have dynamic dashboards and predictive models that highlight trends, anticipate outcomes, and reveal new opportunities. For example, an operations team can immediately identify inefficiencies on a production line, while a purchasing department can be warned in advance of an imminent increase in ingredient prices.

Among the common use cases:

- predicting production bottlenecks before they occur;
- identifying the best-performing products according to regional sales trends;
- optimizing ingredient ratios to reduce costs while preserving taste;
- monitoring energy or water consumption to improve sustainability indicators.

AI also promotes collaboration between departments — sales, marketing, operations — by creating a common vision of what works and what needs special attention. Rather than working in silos, teams can align on updated data, prioritize actions to take, and respond more quickly to market changes. And above all, AI doesn't just indicate what's happening; it explains why it's happening and determines the best course of action. It's a bit like having a real-time strategist integrated into the company. In a highly competitive food industry, with tight margins and rapidly evolving trends, this type of information can make all the difference between reacting too late and staying ahead.

VII.7. Feeding the future : AI serving food security and sustainability

Food security is one of the greatest global challenges — and AI is increasingly becoming an essential component of the solution. From the farm to distribution centers, it optimizes how food is grown, processed, and transported. Climate-aware forecasting tools guide farmers on the optimal times to plant or irrigate. In production, AI reduces waste and ensures that food flows efficiently thru the supply chain, thereby decreasing the risk of spoilage or stockouts. It also enhances transparency. AI systems ensure complete tracking and traceability of products, from their origin to their transformation, which fosters trust and accountability. And in more experimental areas, some startups are already leveraging AI to transform carbon emissions into usable food ingredients — thus linking agrifood innovation with climate goals. In summary, AI is helping to build food systems that are not only smarter but also more resilient and sustainable — for everyone.

VII.8. What awaits us: future trends of AI in the food industry

The role of AI in the food industry is just beginning. What we see today—real-time monitoring, personalized products, predictive forecasting—is paving the way for even more significant changes in the years to come. One of the major trends to watch is hyper-personalization. With advancements in wearable technologies and the integration of health data, we will see the emergence of food products tailored to each individual's genetic profiles, activity levels, or health goals—all thanks to product development and AI-powered

recommendation engines. Another trend is the rise of fully autonomous production environments. Imagine factories where AI controls the entire process — from sourcing to cooking, to packaging — with minimal human intervention. Finally, as sustainability becomes a strategic priority, AI will play a key role in monitoring environmental impact, optimizing energy and water usage, and supporting companies in achieving increasingly ambitious climate goals. The future of AI in the food industry is not about replacing people, but about empowering them to do more, better, and more sustainably.

Conclusion

Global food systems must deliver nutritious, sustainable foods while sharply reducing environmental impact. Yet, food innovation remains slow, empirical and fragmented. Artificial intelligence (AI) offers a transformative path to link molecular composition to functional performance, connect chemical structure to sensory outcomes and accelerate cross-disciplinary innovation across the production pipeline. AI for food constitutes an emerging discipline that integrates ingredient design, formulation development, fermentation and production, texture analysis, sensory science, manufacturing and recipe generation. Integrating AI responsibly into the food innovation cycle can accelerate the transition to sustainable food systems and establish a predictive, design-driven science of food for human and planetary health.

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