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Sustainable Food Processing Inspired by Nature

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Here, we elaborate on the natural origin and use of enzymes and cultures in sustainable food processing. We also illustrate how enzymatically treated or fermented food can contribute to solving challenges involving nutrition and health, such as aging, malnutrition, obesity, and allergy.

Processed Food As a Global Good?

In today's society, processed food can be perceived as less natural and unhealthy [1], and the demand for organic and minimally processed food is increasing. Here, we illustrate how principles inspired by nature (processes and mechanisms used by living organisms such as plants, microorganisms, or animals) can be translated to food processing to produce nutritious and tasty food that can be used to combat global health challenges, such as aging, malnutrition, obesity, and allergy. We also propose that the degree of processing of food is less important to evaluate than are the health contribution of the processed food in the daily diet and the environmental impact of the processing.

Food Enzymes Inspired by Nature

Enzymes exist in all forms of life and, as biocatalysts, they enable specific chemical reactions to occur more quickly by lowering the activation energy. Enzymes are present in many unprocessed foods, such as raw fruits, vegetables, nuts, seeds, and animal-derived products, and they are often used in food processing for similar purposes as in nature. Typical natural enzymatic processes involve lipases, carbohydrases, or proteases, such as the germination of grains and the digestion of milk by rennet in young (ruminant) mammals. For centuries, humans have adopted these processes in food preparation: in malting for producing malted beverages and for cheese making, respectively. During enzymatic conversions, nutrients can be released from the raw material and transformed into health-promoting ingredients or into taste- and texture-providing molecules, which reduces the need to use additives.

More specifically, proteases occur in all organisms, from eukaryotes to viruses, and are involved in a multitude of physiological reactions, from the simple digestion of food proteins into amino acids to highly regulated cascades and signaling functions in many living organisms [2]. Natural proteases are applied in food preparation (e.g., as meat tenderizers or to produce hypoallergenic food [3]).

Carbohydrases catalyze the breakdown, conversion, or polymerization of carbohydrates, often with the aim to liberate energy in the form of more readily available mono-, di-, or tri-saccharides, store energy (e.g., as starch or glycogen), or provide structure and protection (e.g., in the form of cellulose). A promising application in food processing is the use of glycosyltransferases to form slowly or nondigestible sugars or fibers, with the aim to better control glucose management and/or reduce calories [4].

Finally, lipases have critical roles in living organisms and are involved in processing lipids for digestion, transport, modulation of membrane integrity, lipid signaling, and lipid rafts. In food processing, enzymatically catalyzed hydrolysis of natural fats can optimize the *in situ* formation (Box 1) of mono- and diglycerides and fatty acids, and they offer a natural alternative for the chemically catalyzed esterification of free fatty acids and glycerol, thus reducing the need to add emulsifiers [5].

Cultured Food Inspired by Nature

A specific category of processed food inspired by nature is cultured or fermented food. In nature, microbes, such as yeast and lactic acid bacteria, convert food raw materials into products with a lower energy density, such as ethanol or lactate. At the same time, they can enhance the nutritional value by producing bioactive compounds and vitamins. Cultured food has been part of the human culinary tradition for thousands of years. While originally used as a method of natural food preservation, fermentation is also used today to prepare food products with health functional properties and taste [6]. Well-known examples include yoghurt and kimchi. Besides the *in situ* production of vitamins, the fermenting microorganisms can also remove toxins from crops such as cassava, which naturally contains the toxin linamarin, and/or enrich cultured foods with short-chain fatty acids, which are important for gut health [7]. Finally, cultured foods are known for their more complex taste and mouth feel, making them a valuable part of a palatable and healthy diet. A specific category of cultured food is probiotic-fermented food, where, during fermentation, the concentration of probiotics (living microorganisms conferring a specific health benefit to the host when consumed in adequate amounts) increases [8]. Interestingly, one recent proposal suggested including fermented foods, which are often present in traditional products from Asia, Africa, and South America, in food guides around the world, including more westernized societies [6].

In nature, many microbes seldom exist independently from other microorganisms, and they often work in concordance when processing complex substrates (a process called 'co-metabolism'). With few exceptions, food fermentations also rely on mixed cultures of microorganisms, such as the production of yoghurt [9].

Box 1. In-Process Formation of Food Attributes

Treating food raw materials with microorganisms and/or enzymes, eventually in combination with thermal processing (as often happens during cooking), can be used to produce valuable ingredients that can be added to raw food material. However, fermentation and enzyme technology can also be used for in-process formation of targeted quality attributes, such as flavor, color, texturizing agents, preservatives, antioxidants, or other bioactive molecules, thus unlocking the full potential of raw materials and natural ingredients without the need for (artificial) additives. Figure I illustrates eight different ways of how fermentation and enzyme technology can be used in food processing, either for producing ingredients or for in situ formation in the final food product.

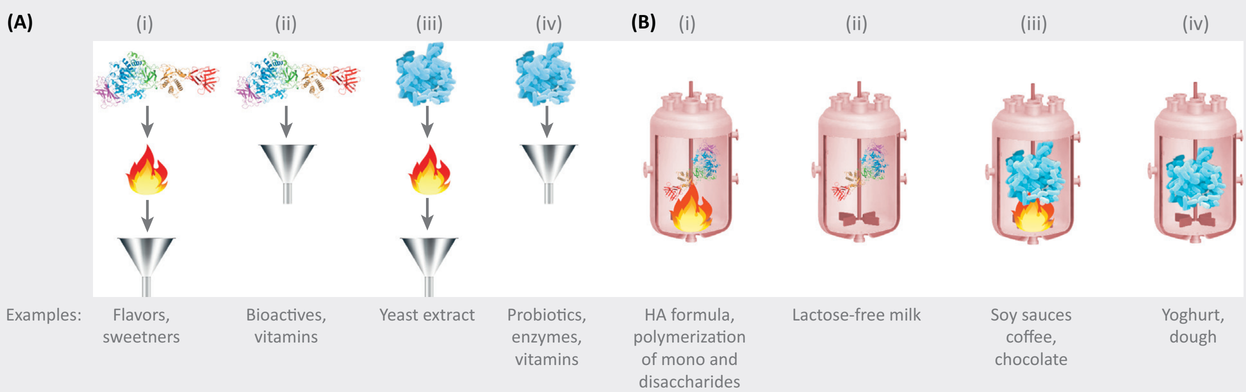

Figure I. Illustration and Examples of Eight Different Ways of Bioprocessing for Production of Functional Ingredients in Purified Form (A) or Generated During Processing (B). (Ai) Enzymatic treatment, heat treatment, separation and/or concentration; (Aii) Enzymatic treatment, separation and/or concentration; (Aiii) Fermentation, heat treatment, separation and/or concentration; (Aiv) Fermentation, separation and/or concentration; (Bi) In process enzymatic treatment and heat treatment; (Bii) In process enzymatic treatment; (Biii) In process fermentation and heat treatment; (Biv) In process fermentation. Image of glucansucrase provided by L. Dijkhuizen and team; Image of *Lactobacillus paracasei* provided by C. Loussert and team.

More convoluted consortia of microorganisms occur during the natural fermentation of cocoa- or coffee beans, which provides opportunities to apply mixed starter cultures to prevent spoilage and ultimately steer the nutritional quality and flavor of foods, such as chocolate or coffee [10].

Bioprocessed Foods Enhance Health and Sustainability

Table S1 in the supplemental information online lists examples of how food processing using enzymes or cultures can offer solutions for global nutrition and health issues, including aging, malnutrition, obesity, and allergy. Furthermore, the use of enzymes and cultures in food processing can be more environmentally friendly compared with traditional processes. For instance, water and energy are saved during the production of malted barley by applying germinating enzymes on green barley for generating malt in-process (Box 1) [11]. Chymosin, produced by bacteria, fungi, or yeast, is a more animal-friendly alternative to producing cheese with rennet sourced from calf stomachs [11]. Although controversial, the production of ingredients such as stevia and vanillin by genetically engineered organisms has a smaller impact on the environment compared to that of physical extraction processes from plants [12].

How Should We Evaluate Processed Foods?

Food can be processed to improve nutrition and health, but processing may also reduce the nutritional value of the product [13]. Even if certain processes occur in nature, this should not automatically justify their translation to food processing. Apart from potential safety concerns (Box 2), it is also important to consider the potential impact on health. For instance, depending on daily consumption patterns and needs, a too-high intake of mono- or disaccharides obtained from enzymatically treated starches, or a high consumption of ethanol produced by fermentation, could lead to excess calorie intake and increase the risk for so-called 'lifestyle' diseases. Nevertheless, it has also been reported that the processing of food itself does not correlate with health indicators, such as body mass index [14].

To create a more substantive debate about the naturalness and healthiness of processed food, we propose that, rather than judging the nutritional quality of food on the degree of processing [1], discussion and evaluation should focus on three elements: (i) the evidence-based nutrition and health-related contribution of the processed food in the daily diet; (ii) the natural origin of the processing; and (iii) the total life cycle assessment of the food product, including its processing and generated waste streams. All of these elements should be compared with the alternatives. Therefore, educating the general public on nutrition, and transparency about why and how food is processed and where it comes from, remain essential.

Box 2. Assuring the Safety of Food Processing Inspired by Nature

Although enzymes and cultures can be used to make food safer (e.g., Table S1 in the supplemental information online contains the examples of acrylamide and mycotoxins), food safety principles for food processing inspired by nature should be addressed in hazard analysis and critical control point (HACCP) programs, as with any kind of food processing. More specifically, enzymes should be checked for potential allergenicity and for their potential to generate side products, before and after eventual further (thermo) processing. Cultures used for fermented food should not cause harm through toxin production or the presence of antibiotic-resistance genes. Food safety authorities, such as the US Food and Drug Administration (FDA) and European Food Safety Administration (EFSA) require that food additives, including enzymes or cultures, have a generally recognized as safe (GRAS) or qualified presumption of safety (QPS) status, respectively. The use of GRAS or QPS starter cultures can also help to make traditional fermentation processes safer, especially when they are sensitive to contaminating microorganisms.

Concluding Remarks and Future Perspectives

In today's society, processed food often has a dubious connotation. On the one hand, there is a trend toward rejecting processed food in favor of natural and organic food. On the other hand, processing can assure that our food is safe, prevent spoilage and waste, and increase its nutritional value. Here, we have illustrated that the use of enzymes and cultures in food processing is inspired by nature and can be done on a large scale, providing solutions to challenges involving nutrition and health. Enzymes and cultures can also be used to produce food ingredients with a lower energy footprint compared with traditional processes.

We expect that the future of enzymatically treated or fermented food inspired by nature will follow three paths. First, traditional starter cultures for fermentation purposes, as well as enzymes extracted from pure natural plant sources, such as pineapple or papaya, will be more broadly used. Second, enzymes will increasingly have enhanced technical properties, such as better thermostability and faster reaction rates [11], whether obtained after adaptation and selection, or sourcing from, for example, extremophilic microorganisms. Third, genetically engineered microorganisms and enzymes with improved technical properties will increasingly be used to enhance health benefits (Table S1 in the supplemental information online). Although a thorough discussion of genetic engineering and all of its pros and cons are beyond the scope of this article, the evolution, adaptation, selection, and survival of natural traits in a specific environment are a consequence of naturally occurring modifications of DNA of organisms. Sometimes genetic modification is even embedded in the survival mechanisms of bacteria in form of transposons and CRISPR/Cas systems [15].

We conclude that the final cost–benefit analysis of food processing inspired by nature depends on a total evaluation of its advantages and disadvantages versus the alternatives. Besides taste, which obviously is a key driver for the acceptance of food, this includes assessing the nutritional and health benefits generated for the consumer, sustainability, social impact, and freedom to operate. Establishing this more holistic view on food biotechnology inspired by Nature will help to create a balanced and accepted approach for society, environment, and the economy.

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