Biotechnology-Inspired Solutions to Further Increase Sustainability and Healthiness in the Bakery Market

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ABSTRACT

Biotechnology makes use of living organisms for the production of sustainable, biobased food, feed, fuel, and materials. Biocatalyst enzymes, used to improve the process or product quality of food, are a key example of how industrial biotechnology can be used to help address climate change and resource scarcity. In the bakery market and along the baking value chain, various biotechnology-inspired solutions have already been implemented to reduce the carbon footprint by reducing food waste and loss, lowering energy consumption, and creating clean(er)-label products. Some challenges still remain, especially in realizing sustainable solutions for growing market trends, like healthier or organic baked products.

In 2015, all United Nations members agreed to bring "peace and prosperity for people and planet, now and in the future" (29). This objective was translated into 17 sustainability development goals to be reached by 2030, such as zero hunger, good health and well-being, and responsible consumption and production. To reach these goals, innovation and collaboration are essential. This article demonstrates the potential role of biotechnology to further increase food security and improve health and sustainability in the bakery market.

In the global food system, the challenges are abundant, with reducing food loss and waste being one of the most important. Globally, one-third of food is thrown away, lost during storage or transport, or wasted by retailers or consumers. Not only does this lead to a reduction in food availability and security, it also requires additional food production to compensate for the loss (13). In developed countries, most food waste occurs at the end of the value chain (the consumer), while the opposite holds true for the developing world, where the share of losses during production and storage is larger (13). The combined food waste and loss generates 8% of global greenhouse gas emissions. Based on caloric content, cereals make up the largest share of global food loss and waste (13).

Biotechnology can offer solutions to reduce food loss and waste along the value chain, from production to consumer. In biotechnology, microorganisms such as bacteria or fungi or biocatalysts like enzymes are used to generate products and processes. Industrial biotechnology can be used to make biobased products in sectors such as food, feed, and fuels. In doing so, it uses renewable raw materials, making it one of the most innovative approaches to developing a circular, biobased economy. Many biotechnology-inspired solutions, such as enzymes, have already been developed to minimize food losses using low-carbon emission technologies. In addition to the functional benefits enzymes can provide, the same technologies are applied in the development of new products for growing markets, like organic and healthier bakery products. An overview of the general benefits is provided in Figure 1. These benefits are listed Table I together with the problems they can be used to solve and potential feasible biotechnology-inspired solutions. Each of these topics will be discussed in more detail, with a focus on if and how each of these trends affects sustainability along the value chain.

Reducing Food Loss and Waste

Bread is a staple food for a large portion of the world's population. Although the carbon footprint for bread production is relatively low (0.7 kg CO_2/kg bread, from seed to retail [5]), it does result in high waste. About 10% or more of bread is thrown away by retailers or consumers (5). Waste prevention in the case of bread, thus, would strongly impact the overall life-cycle carbon emission of this food product in a positive way (5,11).

The main causes for bread waste are staling and microbial spoilage (15). Bread staling involves a range of physicochemical processes that negatively impact the texture of bread during storage, reducing its appeal to consumers. During staling, the bread crumb becomes firm and dry, whereas the crust turns tough and leathery. Starch recrystallization is commonly de-

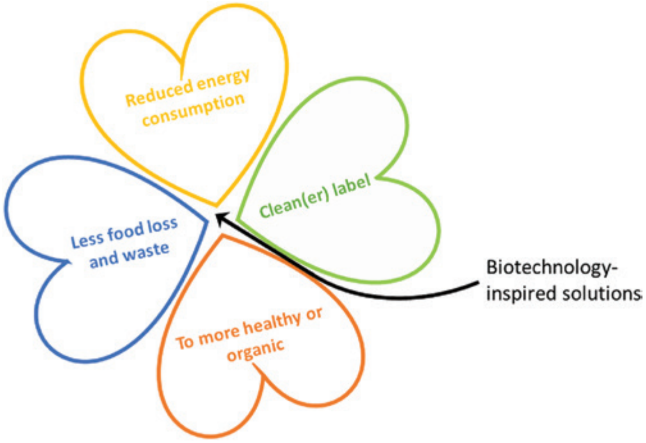

Fig. 1. Overview of the various ways biotechnology can offer sustainable solutions in the bakery market.

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Table I. Overview of some solutions, mostly developed and produced by industrial biotechnology, to challenges along the baking value chain for sustainability-driven trends

Trend	Potential Solution	Approaches to Make Solution Feasible
Reduced food loss and waste	Minimize bread staling	Maltogenic amylase, interrupted baking processes
	Reduce mold growth	Natamycin, bacteria culture
	Use of lower quality flours	Xylanase, oxidase
Reduced energy consumption	Reduced water use	Protease, xylanase
	Reduced mixing time	Oxidase, phospholipase
	Reduced baking time	Protease, xylanase
Clean(er) label	Alternative for chemical emulsifiers	Phospholipase, xylanase, oxidase, amylases
	Alternative for chemical preservatives	Bacteria culture
	Reduction of egg (in cake)	Phospholipase
More healthy or organic products	Whole wheat baked products	Xylanase, cellulase, amylase, lipase
	Reduction of fructan oligomers and polyols	Invertase
	Acrylamide reduction	Asparaginase
	Organic baked products	Some classical enzymes

scribed as the major determinant of the staling process (8). One of the most effective ways to stop this process (and thus prevent staling as a source of food waste) is through the addition of a maltogenic α-amylase enzyme (9). The first generation of maltogenic amylases were aimed mainly at crumb softness. More recent generations go a few steps further and keep the overall freshness of the bread (which goes beyond softness to include moistness and flexibility) as stable as possible over a longer storage period. More in-depth information on the staling process and the impact of this type of enzyme can be found elsewhere (8,22).

Another way to minimize bread waste by retailers (or consumers) is by interrupting the baking process to produce a freshly baked product only when it is needed. Frozen dough or parbaked (partially baked) bread are examples of such adaptations to the breadmaking process. Freezing dough comes with additional challenges regarding flour quality and yeast viability (23). Therefore, the market for parbaked breads is growing quickly. Because more and more bread is sold at retail, such as in supermarkets, parbaking offers an especially valuable alternative. The parbaking process involves two baking steps. The first baking step takes place immediately after mixing and fermentation and lasts for about 65% of the baking phase, reaching an internal crumb temperature of more than 90°C. This suffices to set the crumb without forming a crisp crust (14,23). The bread is then intermittently stored, most often in the freezer, until the final bake-off stage. For shorter periods of time, parbaked breads can also be stored at room temperature or in a refrigerator. The final baking phase takes place at the point of need, for example in a retail store when the bread supply is running low. This second baking phase is shorter, and internal temperatures in the crumb are typically around 70°C. Even though such adaptations of the baking process increase convenience and partly reduce bread waste at retail, they do not necessarily lower the carbon footprint over the bread production life cycle, as they require more storage capacity, increased energy, and extra transport. Only by avoiding food waste completely can these interrupted baking processes become a viable alternative to conventional baking from a sustainability point of view (1).

Microbial contamination is, next to staling, a major cause of bread waste and can account for up to 5% of bread waste in Europe. In more tropical regions, the waste attributed to fungal deterioration can be twice as high at around 11% (30). Wheat flour has low water activity and, thus, is microbially safe. As soon as it is mixed with water during the baking process (which typically takes place between 15 and 30°C), however, microorganisms can proliferate. The heating step in the baking process thermally inactivates the vegetative parts of molds that would be present in the dough. Spores or bacteria, however, may not be killed.

The microorganisms contaminating baked goods are either present in the flour due to wheat harvesting and milling processes, or, as is usually the case, are unintentionally introduced during processing or packaging of baked goods (15). The most common microorganisms known to spoil wheat-based products are molds belonging to the genera *Penicillium*, *Aspergillus*, *Fusarium*, and *Rhizopus* (15). *Rhizopus* is frequently the cause of common bread molds, and *Penicillium* dominates spoilage molds in temperate regions. *Aspergillus* grows faster than *Penicillium* and is also more resistant to higher temperatures and lower water activities. Spoilage caused by bacteria is less common, although thermophilic *Bacillus* species are known to cause ropiness in bread during storage at room temperature (3).

To restrict mold growth, propionic or sorbic acids are often added or formed by bacterial cultures during the breadmaking process, as is the case for some sourdough breads (15). Natamycin is a natural biopreservative compound that is produced through fermentation by the bacterial strain *Streptomyces natalensis*. Natamycin is effective against a broad range of yeasts and fungi (26). The antimycotic function of natamycin is based on a very special mechanism in its interaction with ergosterol (an important building block in the cell wall of molds and yeasts). Natamycin blocks protein transport activity and prevents spore germination, while remaining on the outside of the cell wall (4). This unique mode of action prevents fungi from developing resistance to natamycin, which is proven by the long track record of natamycin use for cheese ripening applications, in which dosage rates have remained stable for decades. Natamycin can be used to prevent mold growth in and on baked products by either spraying it on top of baked goods after they come out of the oven or by including it in the dough for non-yeasted bakery products, such as tortillas. Regulatory approvals for these specific baking applications are limited to several countries.

Apart from the loss of baked products due to staling or microbial contamination, significant losses can occur earlier in the value chain. Environmental conditions during wheat growing, such as temperature and rainfall, and suboptimal postharvest conditions impact not only the microbial status of wheat, but also affect flour composition and, thus, quality. Enzymes, such as xylanases or glucose oxidase, can improve the quality of baked products made from lower quality flours (10,27). More details on the potential of enzymes to improve flour quality at the mill or to adjust dough properties, resulting in better baked products, can be found elsewhere (22).

Clean(er) Label, More Natural Baked Products

The demand for more natural products has prompted bakeries to use fewer additives or synthetic ingredients. In bread, cleaner labels are achieved by leaving out conditioners or additives, which are used in industrialized bakeries because they provide a desired functionality in either dough or bread. The most common emulsifiers used in baking act as dough conditioners or crumb softeners (20). Enzymes are a valuable alternative to these emulsifiers, providing similar functionality, yet with a clean(er) label. Enzymes are processing aids that denature during the baking phase and, in most countries, do not require labeling (27).

Enzymes work on substrates inherently present in the flour and make them more functional. Lipases are often used as alternatives to chemically synthesized emulsifiers, such as DATEM (diacetyl tartaric esters of mono- and diglycerides). Wheat flour contains many different endogenous lipid types and classes. The desired functionality in the baking process is mainly produced by polar lipids. Their amphiphilic nature makes them ideally suited to stabilize the interface and contribute to gas cell and dough stability and, thus, bread volume. Phospholipases are of special interest in this respect. These enzymes remove one fatty acid chain from an endogenous phospho- or galactolipid that has two fatty acid chains, turning it into its lysolipid form, with further improved properties at the interface. In this way, the enzymatically altered polar wheat lipids provide a functionality in the dough, batter, or baked product that is similar to chemical emulsifiers. More information on wheat flour lipids and the use of lipases can be found elsewhere (7,20,22).

As with most enzymes, lipases are used at much lower concentrations than chemical emulsifiers. Thus, in addition to the clean(er) label benefit the use of lipases offers a cost benefit, as it leads to a large reduction in storage and transportation costs and, hence, a lower cost-in-use (7,17). When taking the whole life cycle into consideration, using phospholipase A1 to improve dough stability and volume can lower the carbon footprint more than tenfold compared to using DATEM (Fig. 2). The main contributor in the carbon footprint of the enzyme is the wheat flour added to compensate for the weight of the emulsifier. While enabling a cleaner label, lipases also offer a more sustainable, environmentally friendly alternative to chemical emulsifiers.

In cake, phospholipase A2 can be used to make certain lipids in eggs more functional and, hence, allowing a significant reduction of eggs incorporated in a formulation (7). As egg is the most costly and microbially unstable ingredient in cakes, being able to reduce its use is considered a large benefit for cake producers. Moreover, the carbon footprint of cakes formulated with this enzyme is at least 6% lower than that of cakes formulated without the enzyme and with higher egg contents (DSM, Life cycle assessment of CakeZyme Smart in pound cake, 2017; www.dsm.com/food-specialties/en_US/home.html). Egg is the ingredient with the largest carbon footprint in cake, yet the benefit of reducing it is cancelled out to some extent by the need to add extra flour or sugar to compensate for the egg weight in the cake formula. However, when taking into account the fact that the use of phospholipase A2 in cake also allows for a shorter mixing time (7) and reduces staling (DSM, Life cycle assessment of CakeZyme Smart in pound cake, 2017; www.dsm.com/food-specialties/en_US/home.html), the advantage becomes much larger, especially from a sustainability point of view. Additionally, in a broader context any means to reduce eggs without losing their functionality could also be positive for animal well-being, as it could allow an increase in the percentage of free-range chickens.

In addition to lipases, other enzymes can be used as alternatives to chemical additives to improve flour quality or processing. Flour quality can vary significantly depending on wheat species and environmental conditions during production, and this strongly impacts the end quality of the baked product (28). To overcome some of this variation, oxidants are often added to formulations. Potassium bromate, azodicarbonamide (ADA), and ascorbic acid are some of the best known examples (24,28). The use of potassium bromate and ADA, however, is scrutinized for health and environmental reasons. Ascorbic acid, on the other hand, is prone to price volatility. A similar effect and functionality can be established, however, using enzymes, such as glucose or hexose oxidases or xylanases. These enzymes strengthen the gluten network in the dough and affect the viscosity, resulting in improved dough stability, bread volume, and crumb homogeneity (28).

More label-friendly alternatives exist for preservatives in baked products. Synthetic acids, such as sorbate and propionate, are often added to restrict mold growth. Their functionality, however, depends on the pH of the food matrix and their extent of dissociation (15). These acids can be replaced by a natural alternative that may be more appealing to consumers. Some bacte-

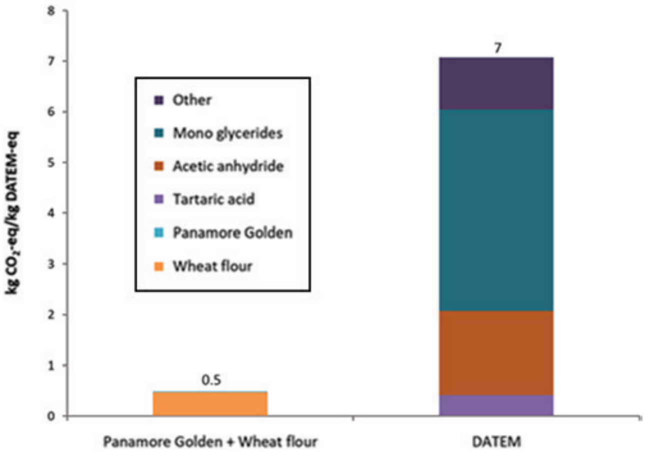

Fig. 2. Breakdown of carbon footprint for DATEM (diacetyl tartaric esters of mono- and diglycerides) versus Panamore Golden, a phospholipase A1 (from DSM), used as an alternative to DATEM to produce dough stability (DSM, Life cycle assessment of Panamore Golden, 2015; www.dsm.com/food-specialties/en_US/home.html).

ria, for example, produce lactic acid naturally during their fermentation in the dough. This is the case in some sourdough breads (15).

Reduced Energy Consumption

Another way in which biotechnology helps to improve sustainability is by offering solutions that reduce energy consumption in the baking process. This can be achieved by lowering the amount of water needed or by reducing mixing or baking times, resulting in an overall lower energy requirement for the process.

By acting on insoluble pentosans, certain xylanases can redistribute water among the various flour components in the dough, resulting in lower water consumption (10,25). Some mild proteases can establish a similar effect in cookies. Protease addition is often undesirable in breadmaking, as a well-developed gluten network is essential for good dough and bread properties. In cookies, however, development of a strong gluten network is not required (and even unwanted) as it may limit cookie spread during baking (21). In this bakery application, mild proteases can be added to reduce the viscosity of the dough, allowing for less water to be used in the recipe. The same principle can be applied to wafer batter. Because proteases result in a lower water content in cookie dough or wafer batter, the baking time in the oven can also be shortened, reducing energy consumption even further.

Other enzymes, such as glucose oxidase, are known to reduce mixing time. Because addition of this enzyme promotes the development of a stronger gluten network, shorter mixing times can be used to achieve well-developed bread dough. In cake batter, phospholipases may also serve to reduce the mixing time (7). The enzymatic formation of lysolipids from flour or egg, improving emulsifying properties, leads to more stable air bubbles. In combination with the possible impact of these enzymes on viscosity, this allows for shorter mixing times in the cake-making process.

Demand for Healthier or Organic Products

Next to a growing demand for more sustainable and natural products, consumers are increasingly looking for healthier products and organic foods. One way to increase the health benefits of a diet is to consume whole wheat bakery products. The bran and germ, removed during the milling process for refined (white) flour, are rich in fibers, vitamins, minerals, and antioxidants. In whole wheat flour, these parts of the kernel are present and provide health benefits to the consumer, such as a reduced risk of diabetes and cardiovascular disease (16). However, there are drawbacks to using whole wheat flour in the baking process since the bran and germ contain more microorganisms, phenols, lipids, and endogenous enzymes. This makes whole wheat flour less stable than white flour. The quality characteristics of white bread, such as large loaf volume, soft bread crumb, and sweet taste, are more difficult to achieve in whole wheat bread, and as such, whole wheat baked products often are less appealing to consumers (15,19,25). The higher lipid and polyphenol contents of whole wheat flour also result in a greater risk for oxidation and rancidity in the baked product (19). Additionally, processing dough made from whole wheat flour is more challenging. The bran fibers require the addition of greater amounts of water and make the dough more difficult to handle. Enzymes can be used to overcome or minimize many of these functional challenges. Amylase can be added to improve fermentation of the dough and softness of the crumb; xylanases and cellulases can contribute to better dough viscosity, stability, and handling; and glucose oxidase can strengthen the dough (19,25). These enzymes all benefit loaf volume after baking as well. Phospholipases can be added to improve dough stability and bread volume, but the higher lipid content of whole wheat flour reduces the benefits of lipases in whole wheat bread. Enzymes, therefore, cannot provide the same functionality as DATEM or other emulsifiers in these bakery applications (19,25). Phospholipases with an increased specificity toward polar lipids over triglycerides (which are present in relatively high concentrations in whole wheat flour) may offer a solution.

The benefits and drawbacks of whole wheat bakery products are also reflected in considerations related to sustainability. Even though using a larger fraction of the grain is beneficial and reduces food losses early in the value chain, the higher instability of the flour, need for more water and extra additives during breadmaking, and lower quality and stability of baked products ultimately lead to more food waste and, thus, a higher carbon footprint for whole wheat bread compared with white bread (12). One process benefit of whole wheat flour over white flour is found in parbaked breadmaking. The high fiber content binds water strongly, which makes the bread less susceptible to damage by ice crystals during intermittent freezer storage of parbaked bread (14).

Apart from the use of whole wheat flour to produce healthier baked products, enzyme solutions can provide health benefits in a different way, i.e., by reducing potentially negative components in baked products. In this respect, invertase can reduce fructan-derived fermentable oligo- or disaccharides, which are described as one of the potential causes of abdominal pain in patients suffering from irritable bowel syndrome (18). Invertase can be added to the formulation, but it is also produced by yeast and lactic acid bacteria during fermentation. In addition, asparaginase is used in baked products to reduce acrylamide—a potential carcinogen that can form during baking of cookies, for example. A heating step in the production process of low-moisture foods containing reducing sugars and asparagine can result in the formation of acrylamide. By including asparaginase in the dough, asparagine, the most important precursor of acrylamide, is converted to aspartic acid, which no longer reacts to form

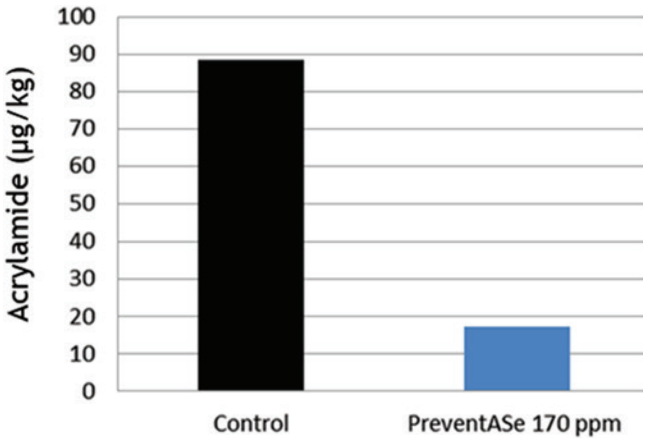

Fig. 3. Acrylamide levels in infant biscuits (cookies) without (control) and with PreventASe, an asparaginase (from DSM), converting asparagine into aspartic acid and lowering acrylamide formation during baking (DSM, Sustainability assessment of PreventASe, 2018; www.dsm.com/food-specialties/en_US/home.html).

acrylamide. In this way, incorporating asparaginase in the baking process can significantly reduce acrylamide levels and, thus, potential health risks, in high-heat, low-water baking applications such as rotary molded biscuits, extruded snacks, and infant biscuits (cookies) (DSM, Sustainability assessment of PreventASe, 2018; www.dsm.com/food-specialties/en_US/home.html). The latter is represented in Figure 3.

The market share of organic baked goods is growing. In these bakery products, only organically grown ingredients can be used. Enzymes or additives, thus, are only allowed when they are not chemically made or modified. No technologies involving genetically modified organisms can be utilized to increase the yield in enzyme production or to make the enzyme specificity better suited for the desired application. Some additives or enzymes with a broader specificity are allowed in the organic bakery market, such as lecithin and classical lipases or xylanases (6). However, no suitable alternative currently exists to retard staling using nonessential ingredients or to improve dough stability in organic bread. The question remains whether these quality parameters for conventional breads also apply to organic baked products, or whether the consumer's expectation for organic breads is somewhat different.

The other consideration that needs to be taken into account regarding sustainability is that although organic farming is eco-friendly and results in a lower carbon footprint per hectare of wheat grown, the carbon footprint per kilogram of bread produced is higher (2). The lower agricultural yields per hectare require a larger area to grow wheat, as well as more transportation and energy than conventional farming to obtain similar amounts of wheat flour. The higher losses during processing (e.g., due to postharvest infestation) further increase the carbon footprint. Moreover, the additives or processing aids that can be used are typically made using a less efficient and, thus, more costly and less sustainable production process. This creates new challenges and opportunities for future biotechnology solutions.

Conclusions

In the baking market, a lot of progress has already been made to reduce food waste, while at the same time making baking labels cleaner and clearer and reducing overall energy consumption without compromising the quality of the baked products. summary of the biotechnology-inspired solutions covering trends toward a more sustainable and healthy baking market can be found in Table I.

Growing trends in healthier or organic foods create opportunities for future developments, especially targeting a lower carbon footprint of baked products.

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