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# Food enzymes in the modern food industry: Benefits, safety, sustainability, and consumer perception

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**Keywords**

Food processing, clean labelling, food enzymes, consumer education, and sustainability

**Abstract**

Enzymes play an important role in the current food production process as they help make anything work better, contribute to the quality of food we consume, and do good to nature. People doubt them even though they are completely natural. It is true that this problem persists because labels are not always clear enough, and consumers sometimes confuse enzymes with synthetic additives. With the increasing number of consumers who prefer "clean labels", it is crucial to be honest, because processed enzymes usually do not end up in food ingredient lists. This paper will discuss how to make use of both natural and modified enzymes and their advantages and safety. The main conclusion is that there needs to be an open discussion about the role of enzymes in the food industry and better public education concerning the issue.

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## 1. Introduction

Essentially, enzymes are specialized proteins that play the role of nature's own enhancers. They are crucial for life and without them, life-sustaining chemical processes would occur too slowly to be effective. Due to the enzymes, the biological processes are sped up so that our bodies can function as they should. Nowadays, they find application in many food processing methods (Yang et al. 2023). Their usefulness is obvious whether it's improving dough consistency, or clarifying juice in the process of food production. Having said that, the use of enzymes contributes to the number of high-quality lactose-free dairy products in the stores at present. Other than their practical usefulness, using enzymes in food production is also the reason for

making the process less harmful compared to the traditional production and is better for nature. The transition to more environmentally friendly way of making production helps producers get higher quality products, mainly due to the better texture and a longer shelf life of the product (Devi et al. 2025).

While enzymes are considered highly beneficial in many applications, people are still not fully aware of what enzymes are, as well as their relevance in the world today. This skepticism stems from being uninformed about the subject, which creates a lot of controversy. Misunderstanding leads to reactions from people who see enzymes as any other chemical compounds created in laboratories or as GMOs. (Kumar et al. 2024). One of the major issues is that product labels are often elusive, meaning that consumers hardly ever get proper and necessary information about what they are buying. There is also the issue of all countries having their own ways of dealing with the matter and taking different approaches to enzymes, and the constant negative portrayal of the subject in the media makes things even worse. Essentially, people have been misunderstanding the tools given to us by Mother Nature as something produced by advanced technology.

Ironically, the global hunger for "clean-label" and organic products has created a wide gap in public awareness and consumer literacy (Table 1). The changes in the industry have surpassed the knowledge needed to increase consumer awareness of the clean-label products. The growth of the market does not offer the clarity that consumers need but rather creates a fog in international markets, keeping people from distinguishing between marketing hype and scientific facts, (Akimova et al. 2024) Moreover, clean-label products utilize the benefits of enzymes for effective production. Enzymes are more than simple additives; they can be used to eliminate artificial emulsifiers and stabilizers with the help of certain enzymatic reactions, which allows producers to avoid using chemical preservatives. As a result, the final ingredient list is much clearer as there are no chemical additives used in the production of clean-label food products (Zhang et al.2022).

**Table 1: Strategies for consumer education on enzymes in food**

| Strategy | Description | Expected outcome | On ground implementation | Ref. |
|---|---|---|---|---|
| Transparent Labelling | Clear explanation of enzyme functions and natural origins directly on packaging | Reduction of hidden additives | Ingredient panels with simplified statements | (Chen et al. 2023) |
| Educational content | Use of infographics, detailed data resource to describe | Enhance acceptance | Information displayed on website, QR or RFID codes | (Dat et al. 2024) |

| | | | | |
|---|---|---|---|---|
| | enzyme's role | | | |
| Interactive Engagement | Workshops, Live QandA sessions, and interaction with consumer | Misconception address, direct dialogue | Essential data and documents sharing | (Devi et al. 2025) |
| Expert collaboration | Collaboration with nutritionist, food scientists | Scientific legitimacy | Public access to data | (FEB, 2026) |
| Sustainability messaging | Highlighting environmental benefits of enzyme use | Appeal to eco-conscious consumers | Eco-gradings | (Grunert et al. 2023) |
| Third party certification | Use of certification to validate enzymes safety and natural status | Availability of external validation | Clean label | (Akimova et al. 2024) |

It is the ability to achieve the equivalent results of artificial ingredients using natural alternatives that defines contemporary clean label science. One of the problems related to food labelling is the existence of a big loophole in the regulation. When manufacturers place enzymes into the category of processing aids only and do not disclose them in the final list of ingredients, they create an information gap that is evident. The fact that the information is not given conjures up not only confusion but also a feeling of disappointment among customers because they expect the labelling to be absolutely reliable. What appears to be a technicality for the industry is seen as a clear intention to mislead in the eyes of the public (Li et al. 2022). Solving this problem requires much more than just a surface-scale reaction from the industry. Stakeholders are no longer focused only on traditional promoting methods. They are tending towards direct interaction with the public and running scientific literacy campaigns. They think that the more informed consumers are, the less likely they will be to doubt new technology. The necessity to speed up the process of transparency has become more crucial than ever. It is not enough for messages from industry players to be technically correct; the wording must also be understandable to a layperson according to (Chen et al. 2023). Instead of hiding crucial information within vague words of industry jargon, involved parties must prioritize communicating in a narrative that is sincere and clear. In the end, if the public fails to grasp the message immediately, the entire educational endeavour is unlikely to succeed in establishing the required trust. Therefore, substantial industry revelations need to go beyond the general terms used. In order to be truly efficient, such transparency must examine the details of production such as fermentation methods which act as the foundation of enzyme production as expressed in the article by (Singh et al. 2022). Beyond the laboratory space, it is necessary to specify how these substances work in the course of food processing.

Ultimately, this story must be backed by solid evidence of the safety data already given. The only way of reducing the current gap in trust is to make sure that the technical qualifications would be positioned in a way similar to that of promotional claims. In turn, present players of the industry are changing their tactics and are focusing on effective methods of education to fill the existing gap in knowledge. The key aspect of this change is the total revision of product labeling practices, and the shift from obscure specifications that cause consumer mistrust. Labeling systems are changing from the general statements of the past to a more detailed and concrete approach to labeling products. Moreover, digital spaces created by companies are changing from informative content to interactive educational spaces. Reforming the labelling system is one of the most critical implementation points regarding the mentioned transition from the obfuscation of lines of communication to the lack thereof. In the past, the absence of transparency regarding product qualities gave rise to uncertainty in consumers. However, the current approach involves significant changes in the nomenclature and thus gives rise to an additional aspect of the organization of corporate ecosystems. Indeed, the redesign of enterprise digital environments has shifted from the traditional use of standard wording to more elaborate approaches that use complicated infographics materials and interesting multimedia in order to avoid the infamy of artificialization (Romano et al. 2023).

The coming of age of the green narrative of enzyme manufacture has placed it at the forefront of marketing. Mere efficiency no longer suffices; the modern customer requires documented proof of the reduction of environmental burden. Enzymes provide a practical alternative to environmentally unfriendly chemical processes by significantly reducing the thermal energy of the process and putting an end to the depletion of local water resources (Sahal et al. 2023). This enables enzymes to overcome one major ethical hurdle in the eyes of eco-conscious consumers, allowing their utility to fit with their commitment to sustainability. This way, the presence of conflicting yet complementary initiatives has given the enzyme technologies a prominent place in the food industry. In this sense, enzymes differ from previous chemical solutions. With their ability to act as green catalysts, enzymes have gone from being niche products to the backbone of the sustainable supply chain (Farhan et al. 2025).

The food sector's future relies heavily upon important transformational aspects of public management regarding the industry's doubts and fears. It is more than data-sharing. To achieve real success, it is necessary to open the modern industry's black boxes so that the factor that used to trigger anxiety becomes the basis of a common scientific awareness. If the attitude of the industry to transparency changes from the concern of PR representatives to being a critical component of the business, it can replace long-term fears with stable evidence-based trust. To meet this requirement, companies need to do more than just commit to some transparency initiatives; they also need to allocate resources to a pedagogical system that anticipates future scepticism that the public might express (Davis et al. 2022).

The topic of authenticity does not just relate to evidence but also to strategies. By promoting a narrative that is characterized both visionary and

scientifically, the industry will be able to change a technology-related issue into a framework that will allow for creating public trust. As consumers learn how to understand modern ingredient lists, their behavior changes accordingly. This kind of openness creates loyalty based on real trust instead of ambiguities. Please note that such educational changes will be the first step in this industry's transition to biological manufacturing (Lusk, 2022).

The enzyme is more than just a biochemical catalyst but the mastermind behind cell speed. These proteins, made by living organisms from within, provide an instantaneous biochemical transformation in living processes. (Kaur et al. 2023). By eliminating the need for a thermal activation for sophisticated chemical reactions, it is possible to achieve the transition from static chemical to dynamic mechanisms of life processes. In practice, it means that production becomes as efficient as that of the living organism and not lagging behind traditional chemistry. The modern industry has abandoned chemical methods in favor of enzymes as the main tool for production purposes. From pharmaceutical manufacturing to the large-scale fermentation process used in biofuel production (Kaur et al. 2023), these proteins provide unprecedented accuracy, allowing for mechanized production of products nowadays. This shift denotes a more extensive transformation to a future in which cleaning formulations and industrial substances are driven by biological efficacy rather than raw chemical input (Goyal and Jerold, 2023).

Although enzymes are integral to nearly every aspect of present-day manufacturing, the prevalence of these biological entities is supplemented by widespread public ignorance (see Fig 1). While consumers conceive of these biocatalysts simply as mysterious entries on product labels, this has created a climate full of kneejerk skepticism instead of reasoned acceptance. This gap between these two aspects is not merely a statistical matter; it is a complete break in technical communication. This gap continues to impede technical literacy, judging from the absence of an adequately relevant story; without this, the food industry runs the risk of having useful advancements discarded as "just processing tricks" by a skeptical public (Lathrop, 2025).

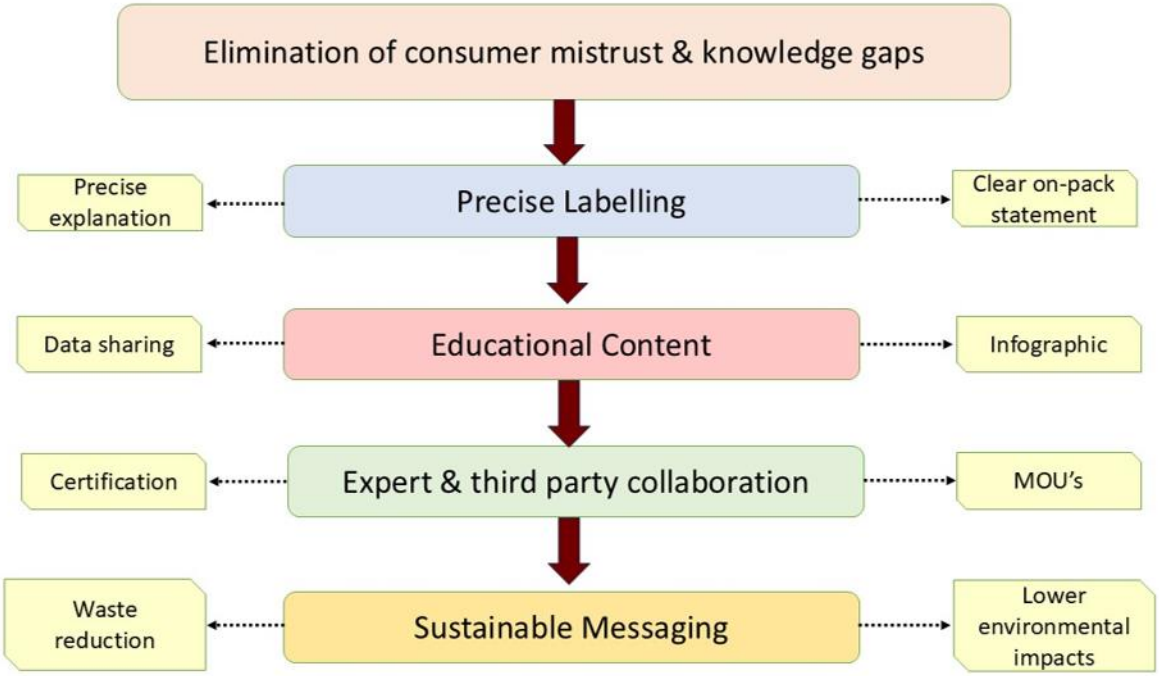



**Fig 1: strategies for eliminating consumer mistrust**

Enzymes are the covert driving force behind modern food processing. From noisy fermentation tanks to materials for building baking dough, these catalytic proteins facilitate different chemical transformations that occur when agricultural raw products are turned into more or less finished products (Awasthi et al. 2025). Thus, they are responsible for the separation of cheese from the whey and for turning the homogenous mash of fruit into a clear juice. Without this level of precision, the supply chain would appear to operate at the pace of biology, which cannot be matched with modern chemistry. Enzymes are not known as the "secret weapon" of the food industry for nothing. Let's take meat processing as a good example. In this segment, proteases help mastering the separation of the tough connective tissues so that difficult-to-cook meat can be made edible. By contrast, the bakery relies on amylases that initiate the breakdown of starches into saccharides, making this biochemical transition vital for crust and crumb creation. This process is more than just a simple reaction; it is a carefully coordinated biochemical process that will determine the final product's texture (Kumar et al. 2025).

The enzyme's use in the food industry is largely unknown to the average consumer. Such lack of awareness is not purely accidental; it is due to an interaction of two regulatory features that allow these enzymes to be classified as processing aids rather than ingredients (Meijer et al. 2026). As a result, the consumer remains totally unaware of the way these enzymes function. The society is much less informed than the processes that shape food production nowadays. As a result, there is much confusion among consumers in relation to the operation of the biological

catalysts. Most consumers are oblivious to the work carried out by these catalysts and do not understand how the food industry benefits from them. In fact, the food industry hides the essence of these processes from consumers in order to justify their use of these products (Meijer et al. 2020).

The public's understanding of the journey of our food is fraught with scientific inaccuracies. This list includes the strikingly common misunderstanding that enzymes are types of chemical additives, a truth that overlooks the fact that enzymes are natural proteins (Silva and Barroca, 2025). This mix-up is not simply a poor retention of information, but comes from a guilty cultural climate where gimmicky sounding ingredients are suspect. Whenever the public fails to recognize the biological origins of these agents, they instinctively categorize them in the "artificial threat" category instead of recognizing that it is merely a natural protein that sustains life. This misplaced perception of enzymes is not an isolated occurrence, but the logical result of being massively uninformed about the subject. The industry has yet to clarify the biological underpinnings and functions of these agents to the public, leaving them with their own assumed technical fears about the "black box" (Hassija et al. 2024).

Even though this procedure is nothing more than a state-of-the-art way of brewing beer or baking bread, most people find it hard to digest the complicated terms involved. They confuse these natural cellular interventions. The result is a marketing fiasco of letting the mechanisms of microbial production remain a "black box". As a result, the industry has sacrificed the technical effectiveness in exchange for public anxiety regarding what it sees as "laboratory-created" dangers. It is clear now that breaking the silence of the public is no longer optional but obligatory for the bio-industrial future. While these catalysts match very well the contemporary idea of low-impact manufacturing, their true potential is still hidden behind consumers' skepticism walls. In order to create a sustainable future, one should not simply rely on advanced proteins but create a story that would teach public how organisms work and the necessity of such knowledge (Bukovnik and Torkar, 2025).

In essence, modern medical science has employed enzymes as biological engineers. Their most obvious role is to break down food in the digestive tract, but they also have a larger scope of medicine. With their help, doctors can make huge biochemical changes within specific treatment protocols. Enzymes are the gears of recovery which make it easier to bring about changes at the molecular level; this cannot be done with the use of chemical drugs. A case in point is the treatment of pancreatic insufficiency. Instead of suffering through uncolored and/or digestively problematic illnesses, people in need can benefit from the use of enzymes. This is true biological hacking, according to FDA. The same idea is evident from the use of lactase in the treatment of lactose intolerance because the use of these enzymes allows patients to drink milk with no problems whatsoever (Khalid et al. 2024).

The typical consumer knows very little about the nature of the protein biotechnology at work here themselves. Instead of immersing in dry academic papers, consumers instinctively pay attention to the flashy "puffery" of advertising campaigns. This might be interpreted as a lack of curiosity, but this is in fact a

logical consequence of a culture that places more value on glitzy marketing campaigns than on biochemistry. In today's world, it is not enough for the bioproduction industry to simply locate the gap between laboratories and supermarkets—it has become a matter of great necessity for the future of bio-industry (Jacques, 2020). If the bioproduction industry wants to enable consumers to overcome their anxiety related to this technology and start applying it, a move from vague marketing ideas to educational materials is needed. By explaining how protein catalysts actually work, we switch from the unawareness of consumers to their expert understanding of these biotechnological applications (Gonlepa et al. 2025).

These biological engines do more than just optimize our industrial activities—they form the actual basis of a new era in industry, replacing harmful chemical processes with natural enzymes that allow us not only to check the "sustainability" box but also to protect the planet from our activities. It marks a pivotal biological transition since the discussion moves from basic manufacturing efficiency to the bitter realization of whether we can survive ecologically in the long run. The laundry room has turned into a quiet laboratory of bioindustrial precision. Modern laundry products do not need boiling water for efficiency; they rather employ proteases and lipases to do the dirty work. These proteins are responsible for all the "fighting" against stains; due to their activity, it becomes possible to save some energy and increase energy efficiency of laundry processes generally by heating less water. As a result, the household carbon footprint has dropped dramatically (Olempska-Beer et al. 2022).

On account of that, we should note that there has been a fundamental change in what we do. Instead of just using brute force of chemical reactions, we are now using the precision of biology to get work done, which means that green technology can be as effective as it is smart. And unfortunately, the majority of potential market players don't see those green advantages behind method of manufacturing (Zhu et al. 2023). Since the sector has failed to explain how the process works, consumers find it hard to make the right choice. It's important to admit that nobody is making wrong choice as a result of bad intentions. It's merely ignorance. The lack of information is what stops the market from becoming sustainable (Jalonen, 2024).

Trust is not something that can be simplified by using fancy PR messages. According to (Bindslev-Jensen et al. 2023), it's a difficult result of real biological literacy. The new telling of the story is about moving from the "black box" approach to one, in which people are treated as adults, who understand science and technology. By breaking the silence, it would be possible to go from fear to real knowledge in the field of biocatalysis. Customers prefer practical information to marketing slogans. Information provided by (Precup et al. 2024) proves that the trust of consumers appears mainly thanks to the transparency related to the origin of these products. When the sector stops hiding behind complicated words and starts giving people raw data, the likelihood of acceptance of this innovation will rise. We cannot expect consumers to traverse through a bio-industrial environment with blindfolds on their eyes. In order to change this lack of information, we need to have a significant transformation towards a high level of clarity. It should start from labels that are sincere and can be easily comprehended by ordinary people. Then

the next step should be carrying out large-scale campaigns that remove advertisement traps. Finally, the most long-lasting solution should be giving children an elementary knowledge about bio-sphere basics starting from the school (Giridhar and Neeraja, 2020).

The clean-label movement has truly uncovered the previously hidden privacy of the industry. Consumers now want more than just vague ingredient lists; they want to see the complete process of how the food they consume is made (EC, 2023). This is a drastic turnaround in terms of food quality. Instead of relying on marketing gimmicks, consumers want to have the data that backs the food in question. Enzymes should no longer be considered an ordinary industrial additive but should be seen as a key biological element. They are more than just “eco-friendly” ingredients. Ultimately, being in tune with the consumer’s moral compass not only completes a “clean-label” checklist but also makes a product an obvious selection. By aligning with people’s values, the sector no longer needs to compete for shelf space but can instead conquer the market (Sheldon, 2022).

The global regulatory framework is an absolute mess of contradictory regulations. If countries require different labels, not only does it frustrate producers, but it also leads to the situation where consumers are bewildered with clashing information. It makes it impossible to give a clear answer to consumers' questions about the product used in making a specific product (Woodley, 2023). In some cases, the use of biocatalysts is ignored in labeling although their role is crucial for producing the item. Other countries, however, demand that everything in terms of ingredients is indicated on the product label. What is meant by raw transparency, when these agencies choose not to take any “functional” exclusions, the result is an ingredient list that is a full “molecular” map instead of a collection of select ingredients (Jadhav et al. 2024).

Implementing one-world regulations that assure truthful labeling is the only exit strategy for consumers who wish to be free from uncertainty. Thus, in order to put an end to being in the dark in stores, it is necessary to have a globally accepted notion of the specification that will change the vagueness of legal terminology into raw truth. This is not only a matter of institutional transformation but also a matter of survival of the industry in the long run; being honest in a labeling area will lead to the reversal of the situation when professional language was widely used in all products instead of developing a true relationship with consumers (Gai and Puntoni, 2021).

In the end, it all begins with a biological blueprint. Achieving an understanding of enzymes isn’t just an educational pursuit. When consumers understand the molecular mechanisms of what they buy, they stop being susceptible victims and start to act independently. Being on the forefront, however, can do much more than just ensure a company stays relevant. It sets up processes for a new round of innovations that actually care about a consumer. Instead of just complying with the “green” standard, this development shows that we can establish a marketplace in which a healthy planet and a healthy society are the same things (Clark et al. 2022). Simply because we speak in jargon doesn’t mean that customers will feel secure. Nor is it about creating a chaotic grow list of ingredients, illustrating it with terms of biology and chemistry. It is important to reach the point where individuals begin to

"understand" science, which prevents them from guessing at the store shelves.

**Drawing the Line: When Nature's Chemistry Stops and Lab-Created Designs Start**

Enzymes are much more than "natural tools." In fact, enzymes play crucial roles as unseen but bright workers in the economy. By acting as nature's own swift machines, enzymes have completely changed the way we manufacture everything from bread to fuel. From now on, instead of simply "borrowing" enzymes from nature, it is possible to "build" enzymes in the laboratory. By squeezing plants, processing animals, or cultivating bacteria, the industry was utilising nature's biological toolkit (Hoyos et al. 2022). Because of great advances in synthetic biology and protein engineering, we are no longer limited to the types of enzymes developed by natural selection. In this regard, an enormous change of power has occurred. Today, we can design personalized biocatalyst from scratch. Our laboratory-made machinery can withstand temperature and chemical treatment which destroy natural proteins. When this "biological limit" is crossed, we enter a new manufacturing era where we can create inventions that seemed impossible before. You need to look beyond scientific terms. One thing is to get an enzyme from nature and another way to make it using computer technologies. If you do not consider this distinction, it means you are making assumptions around it (Dothan, 2025).

Mother Nature has no need for hard hats and high-tech labs to produce the high-speed gears that make these enzymes. These proteins are naturally created in the cells of plants, animals, and microbes. This is their natural birth. Because they've grown in these living organisms, they do not lose their original biological design. Because they grow naturally, there's no need to create vast power generation. Natural enzymes do not need to be treated with boiling heat, unlike many industrial chemicals. They grow and survive in very mild conditions, where there are no extreme conditions (Lubeck and Lubeck, 2022).

Therefore, they operate very quickly and precisely. They're often described in manuals and textbooks; they work in laundry detergent and food processing plants. They are multifunctional biological instruments, and therefore, the companies are able to create a natural cleaning agent and catalyst. Instead of employing chemical tricks, lactase functions by being obtained from yeast and fungal species to allow for the production of safe dairy products. This is the enzyme that performs the biological "heavy lifting" of eliminating lactose from milk without altering its taste and makes it a gut-friendly option for consumers. The secret behind the efficiency of enzymes lies in their structure. They can essentially be defined as globules of proteins folding into intricate three-dimensional forms serving a function similar to origami (Azulay et al. 2022).

This complexity enables an enzyme to locate a specific molecule among millions in a cell and sets off a chemical reaction faster and more accurately than it could be replicated in the laboratory. Nature has been developing the technique for millions of years. What's the result? Natural enzymes have shown to be tremendously effective as well as swift in their functioning. They are not random in their enzyme activity; on the contrary, they are able to secure their target substrate with an incredible degree of precision.

This is a remarkable feature of the natural enzymes that only Evolution can give (Bornscheuer et al. 2023).

Nature does not always adapt well to factory-type operations. Although enzymes are naturally made for particular purposes, they also come with heavy baggage. For example, they are very delicate. Since they originate in nature, produced to work within the confines of living cells, they inevitably decompose when exposed to extreme conditions, which creates a considerable barrier for mass production. Enzymes are fragile organisms; they were created to work in a neutral setting inside the cell but not in the extreme conditions found in an industrial plant. Thus, when subjected to high temperatures and harsh chemicals, they tend to disintegrate. Furthermore, exposing enzymes to high acidity or alkalinity seems to destroy their operation capacity altogether. The production of these products in large quantities is contingent on utilizing nature's innate manufacturing capabilities (Turner, 2022).

The alternatives basically boil down to letting the vast colonies of microorganisms do the work with fermentation or getting them directly from biological tissues. This is more about biological collaboration rather than sterile creation. The core issue is cost. Such inventions are very expensive, and the actual output is highly inconsistent, with one week offering plenty of this product to another week when the tanks are almost empty. Making reliable production chains in an environment where everything is so costly is extremely difficult. You pay a lot of money but do not get a consistent outcome. Making things worse is the fact that natural enzymes are picky, which proves to be problematic because while their precision is extraordinary in biology, it turns into an obstacle for the creation of the production process. This is comparable to attempting the use of a top-notch surgical laser to clear out a construction site; it is remarkable at performing its designated task but utterly inadequate in a coarse environment where construction tools are needed for the assignment (Illanes et al. 2023).

Unlike their natural counterparts, we have the ability to rewrite their biology, extending and manipulating their functions as required to deal with our industrial waste. This built-in adaptability is a major breakthrough. The limitations imposed on the natural enzymes do not apply to these new bio-catalysts. Whether we need them to perform in environments of high temperature, we can make them heat resistant. We can also alter their structure so that they will survive in abrasive solvents and do not dissolve when used there (Arnold, 2022). Probably the most amazing thing is that we can alter their structure in such a way that they will be able to break down artificial compounds that are not present in nature. By incorporating unusual amino acids into their composition, we can force microbes to accomplish tasks for which they were not originally designed. This is not merely changing the existing method but it also indicates changes being made in the working of a weak protein into a powerful hybrid system which is used in extreme conditions where normal biological catalysts are destroyed easily. This is much more than a modification. Researchers have transcended the traditional limitations set by the science of nature and made it possible to explore a completely new dimension of chemistry (Miller et al. 2022).

Now that we have the ability to create a set of tools from scratch instead of being limited by what nature

gave us. This is like going from a few tools to having access to an entire factory at your disposal. Now we don't have to depend on nature's luck anymore because these synthetic enzymes are designed using computer technology, we are able to avoid possible mistakes. The same change from the old biological harvesting method to the new one means that we don't have to be searching for the natural enzymes anymore. However, the only downside of using synthetic catalysts is that they are somewhat tough to make (Jumper et al. 2022). These ideal tools tend to run into organizational difficulty the moment they exit the laboratory. Nature is still the reigning leader in terms of speed. No matter how advanced we make our labs, these enzymes usually cannot match the pace of nature. We can only make a few adjustments in their chemistry, while the original and natural enzymes tend to surpass our synthetic versions (Buller et al. 2023).

This proves that when it comes to evolution and natural processes, it is much more complex and difficult than it would appear in any computer simulation. The biggest problem is accuracy. Our current technology is not able to differentiate one type of molecule from another with the necessary precision. While it does provide some significant benefits, this technology fails in numerous situations where chemistry is too similar. It is only one thing to create something that would work on a theoretical level; the challenge is to make it capable of distinguishing between the necessary elements and staying away from the unnecessary ones. Getting a stamp of approval from the state for the use of synthetic enzymes is a huge obstacle. People are still very uneasy about the concept of these "human-designed" catalysts causing allergic reactions or even worse, being released to nature and disrupting local food chains. As long as we don't have clear evidence that they won't lead to a biological catastrophe, it won't be possible to mass produce them (Huang et al. 2022).

Nature has provided us with a prototype of a genuinely green industry. One good example is natural enzymes. Enzymes work; moreover, they rot. When they are done performing their job, they dissolve into the soil and leave no hazardous remnants as industrial catalysts usually do. The more synthetic enzymes are produced, the more technological innovation we gain; however, this process is not very eco-friendly at all. Natural enzymes can break down and recycle by themselves, while lab-made ones consume a lot of energy during manufacturing (Chen et al. 2023). What is worse, many of these 'optimized' products still require non-renewable raw materials, which results in the failure of the green idea of biological catalysts. Nonetheless, the divide is slowly diminishing. A number of advances in how we navigate the biosynthetic processes and manufacture enzymes in cell-free environments can completely alter the situation. We no longer just produce pretty good reproductions; it seems like we are able to compete with nature in her own turf. The distinction between the artificial and the natural is melted away. The goal of this research is to design enzymes that are not harmful to the environment. Instead of using harsh and permanent chemicals, we use natural processes to create devices that finish their job and decompose (Renata et al. 2022). This means that our research can shift away from "toxic-forever" chemistry.

In terms of using the tools at hand, universal choice does not exist. In fact, the decision to utilize a natural

enzyme or develop a customized version in the laboratory really depends on the specific job parameters. For a medical procedure that requires surgical precision, an enzyme may need to be taken from nature; on the other hand, a normal industrial reaction may only function properly when using synthetic enzyme. The bottom line is that what's required for the procedure determines the course of action (Bloom and Arnold, 2022).

The advantage of nature comes from the fact that there is a need for a nuanced approach. If the task requires extremely accurate performance, then it's best to rely on natural enzymes. In particular, these biological tools possess the ability to perform a task thanks to the chemistry they know how to carry out with organic substance. However, at the point where the task really turns agonizing, the synthetic enzymes take the upper hand. The process of nature is simply not suited to conditions prevailing in either a chemical vat or a toxic waste dump. Therefore, we need to make something that is more resilient in this situation. If there is a need to break down "unnatural" substances in factories or withstand heat levels that can destroy an ordinary protein, biocatalysts that were created especially for this particular situation become the way to go (Lutz and Bornscheuer, 2022).

Ultimately, choosing between nature and the lab is not just a straight improvement: it is a trade-off. Enzymes derived from nature are undoubtedly the masters of delicate precision but can fail during industrial scale operations because of the harsh heat conditions. Conversely, synthetic enzymes can withstand harsh conditions indeed but hardly have the intelligence needed to identify a molecule in the complex mix of chemicals. The reality is that both systems have their own drawbacks and the winning option is always shaped by the conditions and requirements of the factory floor or clinic (Jeschek et al. 2023).

Natural enzymes are the ultimate champions of speed and sustainability. They operate without producing waste. Laboratory enzymes are just like the "power tools" of the biologic universe; we have the ability to change their structure and perform unique tasks that natural enzymes are incapable of. Thus, the choice is made between nature's unambiguous efficiency and feature-rich custom-built technology. The greatest potential lies not within picking sides but combining both elements together. We are heading towards the era when we will take the experience of nature and modify it for unique purposes as far as using natural frameworks as a base, we are capable of adding some engineered features which will help to maximize the effectiveness of enzymes. Finally, we are not going to replace the original one, whether we are trying to improve our planet or heal the humanity (Sheldon, 2023).

**Discovering Hidden Risks: Our Process for Testing Enzymes for Safety and Toxicity**

Biocatalysts are everywhere, from our food to our soaps, and are known to be some of the most powerful elements of the modern age. But the truth is that they aren't without their dangers. We could possibly risk a public health crisis if there are no strict supervision and control by the proper authorities. Since enzymes are proteins, they carry the major red flag of being able to create allergies. This risk reaches its peak in the manufacturing industry as workers are highly likely to

inhale dust or the vapor during the process (Gonzalez et al.2023). Once these bio-particles enter the air, a small action of manipulating them can erupt into a major health issue. Just to clarify: while this stuff might be considered "natural", they are far from being innocent, and inhaling them immediately reveals their negative effects. Working with enzyme powders is not only a dirty but also a great danger for your lungs. Breathing in these tiny particles in bakeries, laboratories or detergent production facilities might lead to serious conditions such as occupational asthma or lung inflammation. Although these bio-materials seem to be natural products, they can be undetectable hazards for those preforming the production of them (Marco et al. 2022).

Generally speaking, when it comes to the food we consume, enzymes are of no concern because the cooking process renders them inactive before they reach the dining table. Most of the time, when cooking at home or in the manufacturing process, high temperatures do the job of destroying the enzymes, which is a process called denaturation. Even if there are a few that make it through the cooking process, the acids in our stomach further destroy them and provide nutrients in the same way as with any other proteins of our diet (Geranto et al. 2022). We tend to see these enzymes as safe, as they stop being active before entering our gastric system.

However, some enzymes simply do not stop being active after the oven goes off. For those who are highly allergic to the ingredients, it can be difficult to deal with the remaining active proteins that are hidden in the fresh batch of bread. The “allergic ghost” is a big issue for food safety, since a tool for making bread butter should not also make customers sick. Important monitors, like the FDA and the European Food Safety Authority, are not allowing anything involving food enzymes to pass without undergoing a comprehensive safety check. They demand a comprehensive safety check of each of the biological tools before they can reach factories (Bigliardi and Galati, 2022). This process is not just a formality, but rather an assurance that your food does not carry unknown health risks. In reality, regulators are the last line of defense between industry and public safety.

We also need to consider the kitchen in which these enzymes are actually made. If you start with genetically modified micro-organisms, the chances of things going devastatingly wrong are very high. Just one mistake in the process can lead to a batch that has fallen victim to some unwanted biological material that should have never been there in the first place (Sreedhara et al. 2020). It’s a delicate balancing act: you cannot only pay attention to the end product (the enzyme); instead, the whole manufacturing process should be protected from any unwanted intrusion. Our aim is to achieve absolute consistency across batches at all times, and we have to make sure that the production facilities will not be sloppy. To achieve this, we need to use a very tough cleaning process so that there is no possibility of any other kinds of DNA being mixed with the toxins produced and so on (Nilsson et al. 2022).

Menrad (2022) describes such a cleaning process as one where everything is scrubbed extremely well. Indeed, even the smallest leftover impurity can spoil the entire batch. Companies that use enzymes in their production and subsequently discard wastewater are not eliminating merely a byproduct; they are dumping a

mixture of biological waste into our waters. This residue doesn't disappear into the ocean; instead, it accumulates in fish and coral and moves up the food chain, turning entire ecosystems into hazardous bio-traps (Siro et al. 2023).

Safety does not only involve box-checking on the production line. For the sake of workers' safety, companies must put measures in place that go beyond generic rules regarding leak prevention; they must be able to lock every cleaning cycle in place (Gautam et al. 2021). The equipment used by everyone on the floor should be right, but even more importantly, the workers should have a basic knowledge regarding all of the risks involved in the work. Without appropriate training, the manuals on safety will not be of any use as everyone will have to know how to deal with bio-hazards. By swapping dry powders for liquid mixes or tiny protective capsules, we have finally taken the "breathable" out of bio-hazards (Betoret et al. 2011). This small change in how we use these enzymes has almost completely removed the danger associated with lung-damaging dust. Instead of a cloud of micro irritants, workers now deal with stable and safe materials that stay in the right place.

Even though enzymes have revolutionized a wide range of fields, especially medicine and the manufacturing of food, we cannot become complacent due to the term "natural." Ensuring worker health and ensuring public confidence is not a suggestion, but a strict requirement which necessitates vigilant testing of toxins along with careful environmental management (Diplock et al. 2022). Whatever merit could be assigned to any bio-product, it still could not justify the emergence of occupational asthma or pollution of oceans.

**Changing Patterns: The Big Change towards New Ingredients and Fitness**

For a long time now, the grocery shopping process has been going through a huge shift. Nowadays, customers pay attention to the contents of the food products that they purchase. Consumers use terms like "clean label" instead of simply focusing on the convenience of food products (Chen et al. 2022). As a result, most of the customers are now past the stage of junk food consumption and are selecting the food products with the nutritious, natural ingredients. This market change sends a clear message to all the people; they want to live a healthy life and know the truth about the food they consume. Customers are no longer satisfied with vague product descriptions, including only basic details regarding how they were made. They want to see proof and be able to trace every ingredient they buy. As a result, customers are becoming very demanding, forcing corporations to abandon the dirty ways of doing business (Verbeke, 2022).

The "clean-label" approach is a significant pushback against overwhelming and prejudiced culinary science. Consumers have grown tired of worrying about minutes of unidentifiable compounds being part of their food (FEB, 2026). They want food that is basic and wholesome without all the science involved in its appearance. Essentially, they must demonstrate their passion for honesty: consumers don't grab foods that look like some laboratory experiment. If the food appears complicated, it won't be bought. What people are mad about is the advanced food science skilled that has replaced natural food options.

They've moved on from lab-created materials to genuine products like honey, plant extracts, and whole

grains. This is not merely a fad - it shows consumers' desire to know that the food they're eating comes from a field, not a laboratory. When one sees a label with the name of something that can be found in cupboard, one knows that they've successfully appealed to modern consumers (Sharma et al. 2024). People are finally waking up to the fact that what counts is what a product actually is, and that is the driving force behind the clean-label trend Figure 2shows the strategies for consumer acceptance for emerging foods. We're tired of wondering if what we eat is fake or made in a harmful manner.

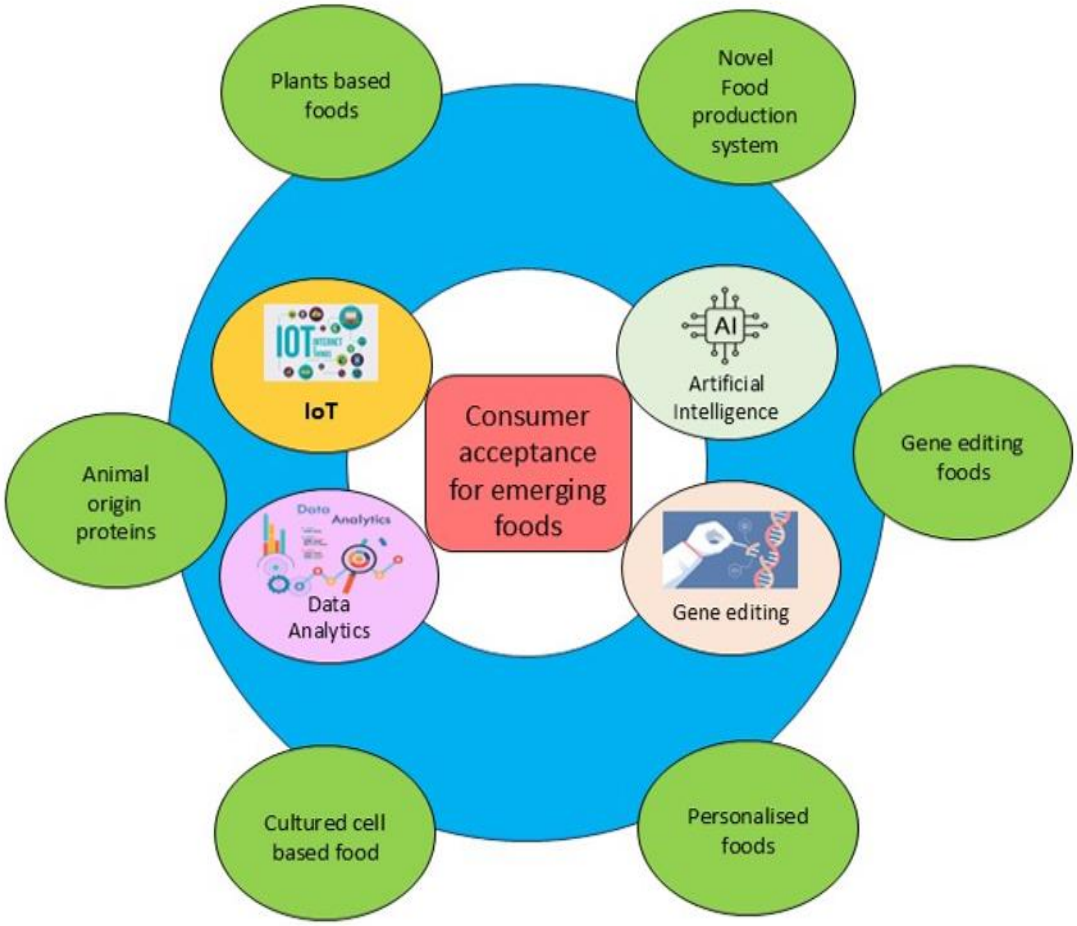



**Fig.2: Strategies for consumer acceptance for emerging foods**

Indeed, functional foods become incredibly popular due to the popularity of clean-label concept because today's consumer wants not only to feel satisfied after having his portion of food but also to acquire some health benefits. In other words, consumers seek for specific health attributes like improved cognitive functioning or improved intestinal flora that cannot be provided by conventional products. The demand for such food reflects people's shift to a new stage of consumption when consumers eat not just to satisfy hunger but to provide some additional health benefit for their body. The main feature of these foods is that they are rich with natural bioactive compounds that have much more benefits for people's health than simple filling of the

stomach. Unlike conventional products, these ingredients contain such elements that can trigger body immunity and protect it from dangerous diseases. Eating these products means taking care of your future health in an effective way. Many examples of such changes in the modern market can be mentioned. For example, there are many products like probiotic yogurts which were designed to improve intestinal flora. Moreover, there are such spreads as plant sterol spread designed to reduce cholesterol level in blood. There are many functional products in beverages as well – it is possible to find juices and even water with additional amounts of vitamins and antioxidants (Jacobo-Velazquez, 2025).

However, everything has completely changed since the emergence of the pandemic. The trend towards leading a healthy lifestyle has been accelerated and has acquired new features. Consumers are no longer just looking for snacks to satisfy hunger – they want ingredients which have certain functional abilities that could act as immunity support. Currently, there is an unprecedentedly high level of concern about preventing illnesses. Also, the stress and uncertainty of recent years have created a new trend that focuses on the health of mind – consumers look for specific food products which will help them maintain concentration and calmness. Besides the development of the trend towards clean label, there is a huge demand for foods which can be called medicinal. Customers are no longer eating just because they want to feel satiated – now, they need snacks and beverages rich in such substances as Vitamin C, Vitamin D, and zinc in order to protect their immune systems. Moreover, in addition to the aforementioned substances, people start adding such herbs as ginger, turmeric, and elderberry to their diet (Manca et al. 2022).

Many people are beginning to see and feel the frightening implications of serious diseases such as cardiovascular disease and hyperglycemia at last. Not a trend but a matter of life and death. Customers are opening their eyes to the realization that what goes into their mouth really does matter. No longer do people just take any snacks or foods that happen to be in front of them. Before their next appointment with the doctor, they are obsessively studying food labels and thinking about their dietary habits. Many people have become picky about what they are eating and how it affects their well-being. They refuse to consume the old junk food with all the unhealthy amounts of salt, sugar, and fatty elements in it. Instead, they are searching for the "real deal" snacks full of fibers, protein, and the good probiotics to keep the body fit. A real revolution has come to the way of shopping. If a food product is not helping you fuel yourself, it is not going to end up in your shopping cart. The brands of food manufacturers know it well and are trying to adapt. They have changed everything in their books and manufacturing processes (Pathak et al. 2025).

Rather than paying lip service to this, these brands are making a real effort to find natural and plant-derived ingredients that people really want on their labels. This is a complete change in how we make food products and have been caused due to the need for transparency in every aisle of our stores. Food manufacturers have begun to shun lab-developed synthetic substances and instead rely on natural techniques like fermentation in order to keep their labels clean. Rather than using artificial products, they use enzymes and natural

bacteria to make sure that the food products taste good, maintain their structure, and remain shelf-stable. This is huge for consumers who desire “natural” foods without compromising on the quality front. In essence, nature does what the chemistry lab was previously doing (Coultate, 2023).

It is not anymore sufficient to read the ingredient labels only because of personal safety. People have understood that they should do it to save the environment. Such unprecedented interest towards the environmental issues is one of the major reasons of the appearance of the "clean" movement. It is quite an obvious change of attitude – the more toxic footprint the product has, the less natural the ingredients are regardless of the number of them. Modern consumers need to know the truth about both the food and its impact on the environment. People start realizing the damage which may be caused by the process of the food production in the industry (Leighton, 2021).

The new attitude cannot be temporary because it changes all the shopping behavior of people completely. Customers are no longer choosing the cheapest product but searching for the brand which cares about soil and fair wages. If the company is lying about its carbon footprint or working conditions, it will not make its way to the basket. There is a moment when "doing good" is as much important as "tasting good". The change of the market behavior happens as a reaction to the shift in thinking about groceries. People stop buying over-processed junk and start looking for the "real food" which consists of strictly plants and is organic. They need products without any additional processing in the factory (Arun et al. 2026).

On the other hand, fulfilling customers' expectations may seem an easy task at first glance. This, however, is not always the case. Meeting the demands of today and tomorrow is quite a complicated task. Being in tune with the emerging trends leads to numerous complications in the industry. Basically, there are too many obstacles in the real world that cannot be bypassed easily. Replacing chemicals with organic alternatives is a costly process. Often brands are forced to replace traditional components with those that will result in skyrocketing production expenses. The challenge here lies in the fact that new ingredients could affect the shelf life of a product or, even worse, change its flavor and structure completely. Making these "healthy" products available to consumers becomes a problem of regulation. On the one hand, it is not difficult for companies to market a snack as something that boosts the work of a consumer's brain. On the other hand, getting the proof that a product meets health standards is a time-consuming process that is not always possible to complete (Deshpande et al. 2020).

Clean label food industry is far beyond being a trend-it is an industry that makes huge money. In 2020, we were talking about a market size of $42 billion, and now the forecast is much higher-something that will surpass $64 billion in 2026. This is not just a little bit higher sales number; this is the complete domination of the market in the era when people care what is inside the box they buy. The desire of consumers all over the globe to consume "superfoods" and healthy snacks is growing exponentially. By 2025, the forecast for this segment of the market will reach $275 billion-a dramatic increase that demonstrates how fast consumer behavior changes. Consumers need more than just nutrition in

their products-they look for some biological advantages, which range from improved digestion to enhanced concentration (Yao et al. 2025).

It is becoming clear that there is an ongoing transformation within the sphere of consumer food purchases. No more guessing games; now consumers demand transparency from food products. "Clean" and superfood trend becomes the reality for the whole food industry as it is not just temporary hype. People become more interested in natural and healthy food, which means that any product that does not correspond to these criteria will not be included in their grocery cart. This growth shows that consumers put their health and the health of the planet before anything else. People are tired of products with unknown components and are looking for goods that provide consumers with genuine and healthy nutrients. Consumers want to make sure that the product is made properly, which means that its production is safe for their health and does not harm the environment. In other words, there is a revolution in terms of consumer needs and their desire to choose food that reflects their views on life and can improve their state of health (Sharma et al. 2024). This transformation leads to complete changing of the food industry standards since all companies face difficulties with high cost and numerous regulations. However, the profit from this process will be tremendous, especially considering the modern attitude of the consumers to marketing tricks. In today's reality, honesty is the only key to success for food products (Marczewska, 2024).

**Monitor the Total Earth-Cost and the Green Barriers to Biocatalysis Utilization**

It is quite often believed that the biocatalysts are a very important instrument in the contemporary food industry. This is mostly due to the fact that they seem to help us achieve higher quality standards at the same time when we increase our production volume, reducing the total amount of the energy required for the process in this way. With the help of the mentioned instruments, producers can boost their outputs not requiring such powerful consumption of the resources as before (Mohammadi et al. 2022).

Nevertheless, even having considered all the benefits of the said usage, it starts to look like the utilization of the biocatalysts is burdened by many environmental risks. There is some evidence that different environmental barriers can emerge when it comes to their production and utilization on the industrial level. Thus, it becomes obvious that their overall impact on the environment needs to be evaluated properly. In order to keep our approach toward the use of the biocatalysts consistent with the basic principles of the sustainable food industry, it looks like there is no other choice but monitor these factors closely. Without doing so, it would become hard to preserve the green infrastructure of the industry (Broumidis et al. 2025).

It can be concluded that the process of developing industrial biocatalysts is strongly associated with the mass cultivation of microbes. It is believed that many technologies may involve genetic engineering organisms, which may imply numerous varieties of bacteria and fungi. As a result of such focus on biological methods, there is a high likelihood that manufacturers prefer the cultivation of microbes instead of synthetic options. While bioconversion methods seem to create less impact on the

environment compared to traditional chemical production, it is commonly assumed that such technology may be characterized by intensive resource consumption. In such a way, it is quite possible that large quantities of electricity, water, and nutrients are to create serious sustainability problems that may remain unnoticed (Zhang et al. 2022). It is quite possible that inappropriate management of such processes may cause serious environmental damage. Taking into account the fact that the source for fermenting media is strongly connected with agriculture products, it can be stated that lack of management will lead to the depletion of natural resources and instability in land usage (Gabriele et al. 2026).

Apart from the actual production, it also looks like handling industrial waste is going to be a challenging problem. There is a good chance that the liquids and residues produced during biocatalyst production are going to need much more control than they usually have. Dealing with all kinds of such waste looks like an important but not very easy thing to do at any contemporary manufacturing plant (Sheldon and Brady, 2021). There is also a good chance that dealing with biological residues and all metabolic waste produced by the fermentation will be very challenging. This is probably one of the most important things if we want to avoid destruction of local ecosystems. Not being able to handle all of these residues may result in permanent destruction of the environment, which will not be easy to fix. It looks like improper handling of the residues is going to be the main reason for nutrient enrichment of the water, or eutrophication (Tiwari and Pal, 2022).

However, the suspicion arises that these practices not only pose one problem but most likely several problems in terms of interferences with the environment in a much more complex way. In all likelihood, it seems like the inability to manage the waste might end up causing irreparable harm in these fragile aquatic ecosystems (Zhang et al. 2022). Often, it turns out that the discussion about environmental safety gets very entangled once gene editing and containment are taken into consideration. Although the use of genetically engineered microbes has certainly allowed for efficient and inexpensive production of enzymes, there has been an unshakable suspicion of the possibility of accidental release among the regulators and general public (Kleba, 2025).

It seems evident that biocatalysts have become an essential ingredient in decreasing the use of harmful chemical processes in the production of foodstuff. As the biological processes are usually performed at the lower temperatures, there is a significant decrease in energy expenses that allow to get closer to the greener technologies. There is a growing suspicion that the certain applications such as the addition of the enzymes into the dough will help to completely avoid any additional artificial substances. Moreover, using fruit-processing enzymes, it seems possible to completely replace the usage of artificial chemicals for clarification of any liquid. Focusing on the carbon emission reduction and resource management, it seems evident that finally, it is possible to implement the sustainable manufacturing techniques. There is a growing suspicion that these factors are exactly those that will define the new era of the green technologies in this sphere of activity (Sharma et al. 2024).

Finally, it seems possible to say that these changes will define the next stage of production development. There

is a growing suspicion that the attitude of the population to the usage of biocatalysts, especially genetically modified organisms, will greatly influence their future success on the market. It seems evident that the majority of consumers prefers products that were produced in natural conditions and do not contain any genetically modified ingredients due to the concern of environment preservation. There is a growing suspicion that the lack of transparency regarding the origin of enzymes may affect consumer confidence negatively (Zo et al. 2026).

There is mounting evidence to show that if organizations fail to embrace renewable material sources as well as closed loop systems, the swift growth of biocatalysts would end up causing more problems than solutions. With the increase in demand, there is an indication that more depletion of natural resources and ecologic strain may arise. Nevertheless, it seems quite possible that the process of converting agricultural waste as well as old food stuffs to fermentation fuels would alter this trend. By avoiding agricultural goods, it would seem like the industry will have found its way to reduce its carbon footprint in a practical way. In this case, it seems like the biocatalyst manufacturing industry is shifting towards greener production processes mainly due to emerging environmental issues. Due to the progress made in terms of synthetic biology and metabolic engineering, it is evident that scientists can utilize safe microorganisms that generate minimal side effects yet maximize the productivity. More often than not, life cycle assessment is employed to evaluate the environmental impact of biocatalysts from production to application (Farhan et al. 2025).

Ultimately, while the use of biocatalysts in food production certainly does benefit the environment, it would seem that the process itself has a series of ecological problems that arise. There is now a growing feeling that addressing these problems will necessitate a far more holistic approach. It looks like we will have to integrate ethical sourcing and efficient waste management into public communications (Zhang et al. 2022). Also, further improvement in biological material processing seems to be the only option to make these technologies sustainable in the long run. It looks increasingly likely that getting everything right means that biocatalysts will become a pillar of the food industry. Ultimately, there is a feeling that such technologies present a means of greening and fortifying the food chain (Rawat et al. 2025).

**Earth-Cost of Enzymes and The Direction That the Research Is Going**

Enzymes and other biological components are simply the instruments created by the Nature. They are eco-friendly, quick in action and very precise in their targets – which is why almost every industry, from food industry to fuel production, tries to use them. As a result of incredible technological breakthroughs, we no longer discover these catalysts; we create them for specific purposes. It doesn't matter whether we need to produce some new drug or to clean the environment from pollution – enzymes do all this job. We have learned how to hack Nature's machines and reprogram protein structure. In the past, we were using whatever enzymes we could find in the wild nature, hoping they will work – but usually they were destroyed by the heat in factories (Sharma et al. 2024).

Now, we are not going to rely on such fragile enzymes,

and we are trying to reconstruct them to become able to endure high temperatures and aggressive chemicals. This is not about simple changes in the structure of these enzymes; this is about creating specific biological tools with zero side effects (Dai et al. 2024). Basically, we have compressed millions of years of natural evolution to just an afternoon in the lab by bombarding proteins with random mutations and then sorting through thousands of samples to look for the “winners,” we have created biological tools that are much more robust than any found in nature. This is a way of avoiding the slow processes of nature and designing custom engines for industrial purposes (Jiao et al. 2021).

Environmental genomics has literally turned the process of finding novel bio-tools upside down. Through analyzing the DNA of soil, water or even intestines of animals, we are gaining access to the great number of microbes that have never been found or grown before. Thus, it gives us an opportunity to discover enzymes, which can survive in Arctic or in volcanic vents of burning heat. In addition, thanks to environmental genomics we have discovered the unique ability of termites to break down the wood because of the presence of special enzymes. That is the breakthrough that makes our tool kit significantly wider for real-life applications. Moreover, we are in the era when we design biologically based systems through combining engineering, computer science and biology. We create "synzymes" that are artificially designed catalysts capable to perform those chemical reactions that were not planned by nature. This is the revolution in such spheres as green chemistry and specialized drugs development since we no longer use the nature to obtain our products but design them ourselves (Ncube et al. 2023).

Putting enzymes onto a surface such as magnets or plastics-like polymers is what scientists refer to as immobilization, which is what comes after industrial biology. The process allows these catalysts to stick to the surfaces where they can withstand tough conditions inside factories. The process of immobilization also allows the enzymes to operate in continuous processes without deteriorating while making it easier to collect the end products because the enzymes are stuck to their support structures. Immobilization has led to a number of benefits including the development of cheaper lactose-free milk production, environmentally friendly biofuel production, and better ways to remove toxins from factory waste water. Mathematics algorithms and modeling have basically blown open the design of biological instruments. In the past, scientists would experiment in the laboratories through trial and error while today the mathematical models provide them with a digital representation of the three-dimensional structure of the enzyme. Just check AlphaFold. The DeepMind program helped produce a high-resolution map of the proteins’ structure which would previously take years to decode, speeding up the entire process of rebuilding enzymes and making it much more cost-effective. This is not only a small enhancement; rather, it is an effective method of getting rid of costly experimentation (Lu et al. 2025).

We are now producing and recycling them in a significantly eco-friendlier manner. Up until recently, production of enzymes meant growing them in massive vats of liquid – a process that was a huge consumer of energy. However, times have changed, and instead of

wasting our resources, we are now growing them in farm leftovers such as husks and stalks, solidly, which not only gets rid of the waste but also increases efficiency by incorporating these renewable resources with efficient processes. Combining various enzymes into one large team is now the only solution to solving industrial problems (Grunert et al. 2023). For example, if we wish to convert wood-based plant waste to the next generation of biofuels, we cannot rely on one single catalyst and hope for the best; we need a combined effort from several enzymes. These enzyme "cocktails" act together in accelerating the process while reducing significantly many intermediate steps involved, (Asioli et al. 2022).

However, to break down wood and gain sugars, three specific enzymes are required that will work together to remove the hard protective layer from it. Today, the food industry tries to meet the needs of producing the "clean-label" products and make it healthier, hence scientists develop new biological tools to be used in kitchens. During the manufacturing of plant-based meat, we use transglutaminase enzymes which allow us to bind proteins and give meat its correct texture. In bread baking, enzymes such as amylases and xylanases are replacing chemical additives because they soften the dough and require fewer artificial components. Also, these enzymes make foods safe and popular by removing gluten and reducing allergens. Hence, biological tools become the basis of successful, clean factories. However, we are not just trying to use what we found in nature but developing new biological engines from scratch using such concepts as protein hacking, lab-made systems, and algorithms. This is a major revolution. It is not only about creating high-quality products but a global movement to an approach that is sustainable (Ramakrishna et al. 2020).

**Food Laws and Being Clean about What We Eat**

Biotechnology is at the core of the process of food production today, performing the function of dough handling in bakeries and clarification of murky fruit juices. They allow us to create milk without any lactose which can be dangerous for people. Since the safety and credibility are so important, all countries in the world have very strict requirements concerning the use and labeling of such catalysts. But it should be mentioned that these laws are different. The great discrepancies that exist between them in various countries prove the fact that different parts of the world have their own vision of food safety and do not develop equally in science (Taheri-Kafrani et al. 2021).

There are two major laws of the European Union which control the entrance of all biological agents into the food chain. Regulation 1331/2008 states the exact conditions of usage of food enzymes. While Regulation 1332/2008 provides the single way of its authorization. It is a very strict procedure. Companies cannot sell such products freely; they have to receive an authorization in the list of allowed enzymes of the EU first. In order to do so, they must first complete an extremely demanding safety assessment by the European Food Safety Authority or EFSA. These specialists analyze the information and verify that the catalyst will not be harmful, induce allergies, or accumulate in the human body in any way. All information must be compiled in huge technical documents before the evaluation can begin (EFSA, 2021).

The EU has some fairly strict regulations regarding what

companies need to disclose on the presence of biological components in your food. If an enzyme is active and carries out its function in the finished product, it needs to be listed (Sharma et al. 2024). However, if it is merely used in the process and plays no part in the final product, labeling is not required for those biological components, leaving a knowledge gap for consumers. The Food and Drug Administration in the United States is the regulator when it comes to food enzymes, and they mostly work with the "Generally Recognized as Safe" approach. If a company wants to introduce a new biological component into their product, it can send a notice to the FDA which will have to prove the safety of that product for its designated purpose through scientific research. There is also an alternative called the food additives petition (Owusu et al. 2023).

It is a very different process compared to Europe. Unlike the EU which has one list of enzymes, the US does not have one. In this case, the company may choose to make a decision on their own regarding whether a catalyst is safe enough or not. Or they may also decide to apply for an optional FDA review to be on the safe side. There is no significant difference between the requirements for the labelling of enzymes used in foods in the United States and the European Union. As far as a catalyst does not affect the food in any way and disappears from it before the consumer gets it, it should not be written on the label. However, if such biological catalysts persist in the food, then they must be labelled (Gupta et al. 2022).

Every biological catalyst used in food products in Canada falls under the exact same regulation framework as food additives. Health Canada keeps an official inventory of authorized instruments, which specifies precisely the origin and conditions of their use. The same as in the U.S. and in Europe, if these enzymes are mere "behind the scenes" helpers, which do not affect the finished product at all, then they do not have to appear on the label. Laws in Asia countries are rather diverse and inconsistent, though. Food enzymes in Japan are regulated by the Food Sanitation Act, as additives, which require an official "green light" for marketing. MHLW takes into account the results of safety testing and investigates sources of raw materials as well as manufacturing process before giving its approval. China works in the same way as Japan (Dai et al. 2024). There are national standards GB 2760 according to which Chinese manufacturers are supposed to use enzymes in food, only certain varieties and only from specified sources. Consumers want to know the exact content of the food that they are eating, and also want to be able to understand the labels (Gupta et al. 2022). The need for this has led to an international drive towards improving the chaotic regulations on biological technologies and improving food labeling.

There is an opportunity for businesses to exclude these "hidden helpers" from the list in order to protect their trade secrets. Thus, there is a kind of legal loophole for companies. However, the business loophole is far from the full disclosure that consumers really need. In addition to the use of enzyme technology in food production, the use of biological catalysts created by genetically modified microbes creates additional problems both in terms of legislation and labelling. The European Union is very strict in this regard. Under Regulation 1829/2003, food and feed products created

using this technology should undergo strict testing; however, in this case, labelling becomes the most important issue (Aversano, 2025).

If even traces of GMO material remain in the product, then the manufacturer is obliged to disclose all information to the consumer. Summing up, the regulation of food enzymes is a complicated balancing act. Lawmakers seek to facilitate the development of science while ensuring the safety of people and transparency of labelling. Safety tests are stringent worldwide, but labelling is another matter. The disclosure standards differ based on the regions, and the majority of customers feels deprived of knowledge about food products. Solving these inconsistencies is the only possible way to ensure that the food industry will be trusted by its target market (Rogerson and Parry, 2020).

**How the food business helps common consumers to get hold of biological tools**

Biological tools, such as enzymes, become increasingly popular in the modern food production process since they shorten the ingredients list, increase the efficiency of manufacturing and even make the snacks healthier. However, there is an issue. Many people are skeptical about biological tools because they are confused with synthetic ingredients or are afraid of unexpected allergies. In order to gain the trust, food corporations started to disclose information openly (Asioli et al. 2022). They start providing more transparent ingredients information and demonstrating that their products are safe for consumption.

Whatever the modern food industry does at the moment can be described in two words – honesty and transparency. People are very interested in healthy lifestyle, and therefore, they demand the complete disclosure of food products. Because of this, the food firms are really trying hard to make very clear information that surpasses everything that is required legally by quite a distance. They are not taking the easy way out through fine prints. Instead, they are using their packages, their websites and sometimes even the shop signs to get the true picture of how biological techniques are used to convert raw ingredients into the food products that we purchase. Rather than use the term “opaque synthetic components,” more bakers and dairy makers are touting enzyme action (Precup et al. 2024).

As for example, lactase, the straightforward secret of producing stomach-friendly milk, and amylase, which makes the bread we buy soft and porous. This is not only about “optimization.” The main idea is to produce foods that consumers will enjoy (Bi et al. 2022). Not only selling but also educating and informing – that’s the new purpose, which allows consumers to feel involved in the process. Nowadays, food production companies are producing lots of different things like video clips and clear charts, in order to clarify the origin of these biological catalysts. They prove that catalysts are usually obtained from natural microorganism cultures and help improve our food safety. They usually collaborate with experts and universities to maintain the integrity of information. Such transparency prevents consumers from worrying about “hidden chemicals,” proving the naturalness of these catalysts and their benefits to the environment (Garcia-Serna et al. 2022).

The most efficient technique to persuade consumers is to simply have conversations with them. Techniques

such as cooking demonstrations, training seminars, and online chats are highly effective because they transform a one-sided presentation into an engaging discussion. With public engagement, businesses will be able to challenge misconceptions regarding food science and address the fears surrounding food science. It is all about being transparent and understanding the concerns of shoppers in relation to the catalysts. Video chat with food scientists or even doctors is very effective for these purposes (Asioli et al. 2022). This way businesses will be able to address complicated issues in terms of allergy risks and environmental impact of the catalysts. When an external body gives a seal of approval to a food product, then trust is built immensely (Gupta et al. 2022).

This label of "simple ingredients" and "natural helper" is more than just branding. It shows that these biological agents are being used in the correct way. Moreover, such seals of approval not only confirm that a certain product is safe but also serve as a guide for the average consumer to learn more about the contents of their food. Collaboration with physicians and nutritionists will help us spread the message as far as it is possible. After all, people listen to their doctors (Lin et al. 2021).

Thus, the latter can explain how the enzyme helps in digestion, removes gluten, and processes milk without pain in the stomach. From simple leaflets in clinics to training sessions at local pharmacies, these experts provide the necessary information. This is about educating consumers how to use these natural biological tools in everyday life. One of the important transformations in the process of education is the shift towards nature. The next major initiative involves resolving the confusion through developing comprehensive global rules and guidelines that will finally make all countries play by the same book. Another important objective here involves making legislation clear and having all countries stick to the same playbook. As mentioned above, currently there is too much variation between legal requirements on information about products offered and this creates a lot of confusion (Zenner, 2026).

Interestingly enough, industry leaders themselves ask for more clarity and propose using clearer terms for describing some substances, such as calling an enzyme "a natural helper" rather than "production facilitator". This, in its turn, will help establish a common approach in labeling. The introduction of global rules will definitely help build more trust. Shoppers will finally have all necessary data in order to make their decisions. However, despite all the initiatives, there will still be some serious issues left. Overcoming people's prejudices is not easy and fast and this task becomes more complicated due to the incorrect presentation of information in media as well as high complexity of science itself (Grunert et al. 2023).

Therefore, it is important for firms not to limit themselves to one letter and to continue working with different approaches and provide evidence. In order to be successful with convincing shoppers about the benefits of the products, companies should focus on integrating learning into their long-term social objectives. It should not become a marketing trick used in order to push shoppers towards purchasing additional products. Educating people about the application of enzymes in foods should be about it. Through clear communication, participation, and providing evidence from specialists, the food industry

will be able to achieve the trust of its clients and make them believers. It works. This is not just an approach that will help to increase sales (Sharma et al. 2024). It is about providing everyone with all necessary information that will help them to choose food according to their own needs.

**A Glance into the Way These Natural Ingredients Are Really Applied**

PureGrain decided to launch an initiative that could finally reveal everything about the way these enzymes work in the case of a simple bread recipe. This brand has earned a reputable name all over Europe due to the excellent quality of its bread produced in accordance with craft standards. Unfortunately, they faced some difficulties after conducting market research. According to it, many customers misunderstood the use of enzymes and considered them to be artificial components or "hidden chemicals." Even though these enzymes are completely natural and used only to improve the quality of the dough and prolong the shelf-life of the bread, many consumers did not see the point of adding them (Haixi et al. 2025). In order to regain customers' trust, PureGrain understood the need for transparency, so they launched an initiative entitled "The Natural Helper Initiatives," which provides straightforward information. Thus, they began by placing an understandable statement on the bag. Namely, these enzymes are just natural proteins that allow maintaining softness of bread without adding any artificial substances. They have also revamped their site with an FAQ page and short videos explaining the source of the enzymes – primarily from natural microbe culture - how the enzymes react in the oven, and how the enzymes completely degrade before the bread even finishes baking (Precup et al. 2024).

Through PureGrain, it became apparent that the usage of these natural agents lies behind the ability to make ingredient labels short. And this is pretty straightforward. As these enzymes take on the role of the heavy lifting, the company does not need to resort to artificial additives only for improving the dough feel. As proof of their transparency, they managed to establish partnerships with physicians, food scientists, and consumer advocates. This collaboration enabled the company to be proactive and host all kinds of activities from in-person cooking classes in the supermarket to live chats on the internet. Customers were able to interact with professionals personally, pose questions, and even participate in cooking activities in person (Gupta et al. 2022).

These individuals took part in cooking trials themselves to witness firsthand the effects of these natural enzymes. Moreover, the company was not afraid to go as far as acquiring a certificate of external independent verification as proof of their authenticity and transparency. In order to demonstrate that they can be trusted when they say something on the label, they used social media for direct. To the customers. Through live chats and video clips of them doing the baking, it is now evident to everyone that they are all natural ingredients that they use. It has truly been a rewarding experience. As seen when the surveys were conducted after the baking session, it is now apparent that the customers got it since understanding of enzymes increased by 40% while trust in PureGrain increased by 25%. Inviting regular customers into the process is what will eventually put to rest those myths regarding using

natural aids in our foods. It is through such involvement of PureGrain that not only have they helped their own cause but have also provided the necessary information for the consumers to make informed decisions according to their needs (Precup et al. 2024).

**Conclusion**

Enzymes are extremely important in making food production sustainable in our environment, but the fact is that people still don't know much about enzymes. To overcome this problem, it is not enough to add information in small print on food packages. What we need is a complete change toward transparent rules. Even though enzymes provide enormous environmental benefits, we shouldn't compromise on their safe use. All in all, winning the hearts of the public is not only about scientific achievements but also about creating confidence through clear communication in the worldwide food industry.

**Conflict of Interest**

The author has not reported any conflicts of interest that may influence the research findings.

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