

Review

Microbial Resources, Fermentation and Reduction of Negative Externalities in Food Systems: Patterns toward Sustainability and Resilience

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Abstract: One of the main targets of sustainable development is the reduction of environmental, social, and economic negative externalities associated with the production of foods and beverages. Those externalities occur at different stages of food chains, from the farm to the fork, with deleterious impacts to different extents. Increasing evidence testifies to the potential of microbial-based solutions and fermentative processes as mitigating strategies to reduce negative externalities in food systems. In several cases, innovative solutions might find in situ applications from the farm to the fork, including advances in food matrices by means of tailored fermentative processes. This viewpoint recalls the attention on microbial biotechnologies as a field of bioeconomy and of ‘green’ innovations to improve sustainability and resilience of agri-food systems alleviating environmental, economic, and social undesired externalities. We argue that food scientists could systematically consider the potential of microbes as ‘mitigating agents’ in all research and development activities dealing with fermentation and microbial-based biotechnologies in the agri-food sector. This aims to conciliate process and product innovations with a development respectful of future generations’ needs and with the aptitude of the systems to overcome global challenges.

Keywords: microbial biotechnologies; biodiversity; fermentation; food; systems; bacteria; yeast; sustainability; resilience; bioeconomy



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1. Microbial Resources and Food Fermentations: The ‘Oldest Biotechnologies’

Microbes, the first forms of life that appeared on Earth at least 3.8 billion years ago, represent the organisms more diffused on the Earth [1,2]. Microorganisms have crucial roles in the environment (cycling of elements and, more generally, of nutrients), in the biology of macroorganisms (of outstanding importance for human, animal, and plant health), and in human advances (e.g., in agriculture, relevant food chains, and biotechnologies) [1,2]. The huge variable in terms of catabolic pathways and for the aptitude to survive to stress conditions make microbes versatile key players on the live planet and drivers of innovations for human activities, such as in biogeochemical processes, biotechnologies, and health [3,4]. Microbes associated with a given ‘macroorganism’ are defined as their microbiome. Microbiomes are involved in critical physiological activities of their hosts, contributing to the maintenance of a state of well-being. The microbiomes associated with plants and animals domesticated for food uses are fundamental to modulate their productivity and affect the quality of the obtained products.

Since the Neolithic period, humans have developed an unawareness of the management of microbes and experience the benefits of food fermentation, also known as the oldest biotechnologies [5], with a vast variability of raw matrices (cereals, vegetables, and bamboo shoots, legumes, roots/tubers, milk, meat, and fish products) and microorganisms

involved (bacteria, yeasts, and molds belonging to several genera and species) [6]. It has been estimated that about one-third of the food and beverage consumption worldwide concern fermented matrices: more than 5000 different products that account for an essential part of global systems [6,7]. In general, a given food/beverage is reported as fermented when is “produced through controlled microbial growth, and the conversion of food components through enzymatic action” [8]. The controlled growth of desired bacteria, yeasts, and filamentous fungi modulate all the main aspects of fermented food/beverage safety and quality (organoleptic, nutritional, functional) (Figure 1) [9].

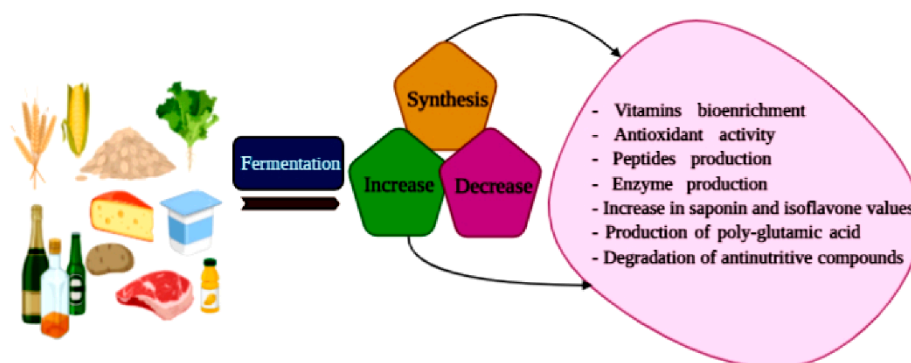


Figure 1. Nutritional enhancement in fermented foods; reproduced from Sharma et al. [10].

In addition, the target of microbial-based solutions has been broadened throughout the advances in microbial biotechnologies. In fact, protective cultures and microbial biocontrol agents can also be found on non-fermented products (e.g., fresh fruits and vegetables, fresh meat) [11,12].

2. Food Systems and Negative Externalities

Food systems embrace all resources and activities related to production, processing, distribution, preparation, and food consumption. Also, food systems include the product market, its institutional networks needed for its governance, and it is the ultimate responsibility for the socioeconomic and environmental outcomes of all the activities listed above [13]. According to Organization for Economic Co-operation and Development (OECD), the term externalities ‘refers to situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided’ [14].

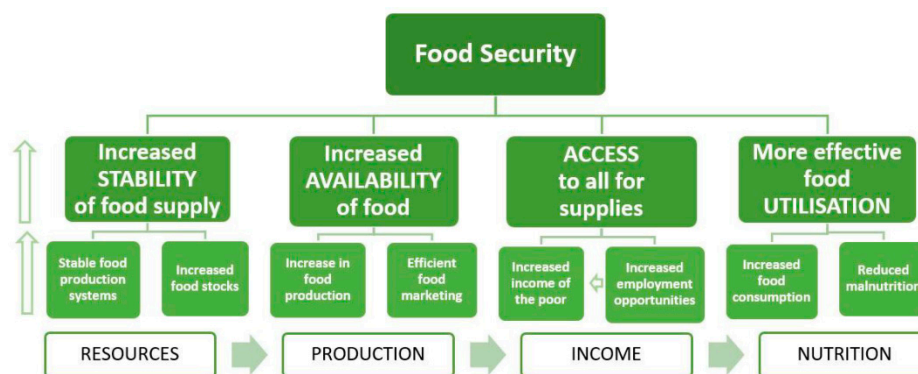
The idea of sustainable development is tailored to mitigate the negative externalities [15]. In effect, these phenomena undermine the pillars of growth compatible with the needs of future generations. For instance, negative environmental externalities reflect into pollution, natural resource exhaustion/degradation threatening the long-term balance of the ecosystem. These trends also threaten the economic sustainability of markets when companies produce limited quantities leaving unsatisfactory market demand as well as whether companies produce low quality or without placing interest in saving energy, water and preventing pollution. Lastly, negative externalities also challenge sustainable development from a social point of view occur if companies produce with the limited observance of the code of good social responsibility practices: for instance, when companies pay unfair prices to supplies exploiting their work, as well as whether they produce unmatching consumers’ and societies’ priorities in terms of animal welfare or workers welfare standards.

The rising occurrence of negative externalities generated by food systems has called into action different sectoral stakeholders, such as policymakers, non-governmental organisations (NGOs), and academics, to prioritise the development of strategies contrasting the environmental, economic, and social externalities generated with the food production. Important examples of initiatives are reported in Table 1, testifying the global interest in tailored policies oriented toward sustainability and food systems resilience.

Table 1. Example of tailored initiatives of policy organisations.

Organisation	Initiatives	Website
United Nations General Assembly	2030 Agenda, Sustainable Development Goals (SDGs)	https://www.un.org/sustainabledevelopment/ , accessed on 13 December 2020
Food and Agriculture Organization (FAO)	Food and agriculture in the 2030 Agenda for Sustainable Development	http://www.fao.org/sustainable-development-goals/en/ , accessed on 10 January 2021
European Commission	Food 2030	https://ec.europa.eu/info/research-and-innovation/research-area/food-systems/food-2030_en , accessed on 14 December 2020
United States Environmental Protection Agency	Sustainable Management of Food	https://www.epa.gov/sustainable-management-food , accessed on 21 December 2020
United Kingdom Government	Food Industry Sustainability Strategy (FISS)	https://www.gov.uk/government/publications/food-industry-sustainability-strategy-fiss , accessed on 20 November 2020

In association with food production, it is possible to highlight several significant negative externalities, ‘namely effects on the environment, the economy and the society that are not reflected in the cost of food’ [16]. These include the release of CO₂ and other greenhouse gases, increase of wastes and pollution, contamination of freshwater, enhanced water deficiencies, soil depletion, a decrease of biological diversity, reduced benefits of microbiomes, the market of unsafe products, diffused antibiotic resistance, lessening of the supply for selected consumers groups, lastly whether the production is foster the rise of socioeconomic disparities [16–20]. Taken together, these undesirable trends threaten food security (Figure 2), human health, environmental resources, and economic networks, especially if we consider future generations.

**Figure 2.** ‘Dimensions of food security’; reproduced from Matkovski et al. [21].

3. Microbial Biotechnologies to Reduce Negative Externalities in Agri-Food Systems

Microbial-based solutions can find global applications in the food systems, counteracting, at the farm level, to relevant negative externalities on a global scale (Table 2). These include, among others, pollution in the animal/plant food chains, diffusion of contaminations, productions associated with and considerable environmental footprints, and reduction of water availability and soil fertility.

Table 2. A non-exhaustive list of possible microbial-based solutions as potential mitigating strategies against negative externalities.

Microbial Biotechnologies to Counteract/Prevent Negative Externalities	Ref.
Biological fixation of nitrogen	[22–24]
Alternative nitrogen sources to be used as feed or food	[19]
Microbial protein production	[19,25]
Microbial biotechnology for CO ₂ capture	[19,22]
Microbial biotechnology to limit diffuse methane emissions	[19]
Microbial-based bioconversion of pollutants in water	[19,26,27]
Microbial-based bioremediation of soil	[28,29]
Microbial biotechnologies for potable water production	[30,31]
Biodegradation of endocrine disruptors from trophic chains	[22]
Optimisation of microbial biofertilizers/biostimulants	[32,33]
Optimisation of microbial biopesticides	[32,34]
Bioprotection and alternatives to antibiotics	[35–37]
Rhizospheric microorganisms for improving the nutrient quality of crops	[38,39]
Beneficial plant-microbe interactions to breed ‘microbe-optimized plants’	[32]
Microalgae and new application in food, feed, and nutraceuticals chains	[40,41]
Microbial-based tailored solutions for sustainable feeding regimen	[42]

As reported in the scientific literature, it is possible to find so many examples as to suggest a potential systemic application of microbes as mitigating agents in the primary production. In several cases, the target is the ‘remediation’ of negative trends: microorganisms selected to reduce carbon dioxide [19,22], bioconversion of pollutants in water via microbial [19,26,27], microbial-driven bioremediation of soil [28,29], and microbial-based decomposition of endocrine disruptors from trophic chains [22]. In addition, we can find ‘green’ microbial alternatives to standard solutions, such as substitute to antibiotic [35–37], pesticides [32,34], fertilizers/stimulants [32,33], feeding regimen [42], nitrogen sources [19], protein production [19,25], and to make water potable [30,31]. Finally, there are positive activities exerted by microbial resources (e.g., biological fixation of nitrogen [22–24], microalgae beneficial application [40,41], modulation of nutrient crops quality [38,39], and breeding of ‘microbe-optimised plants’ [32]) that can counteract to the effects of negative externalities.

4. Tailored Food Fermentative Processes to Reduce Negative Externalities in Food Systems

Moving from the farm to the fork, we shift from general microbial biotechnologies to food/fermentative biotechnologies (Table 3). This technological exploitation of microorganisms can find direct application in food manufacture, with a considerable potential for in situ uses tailored to modulate specific aspects of food quality and, more generally, food production.

The examples reported in Table 3 encompass a broad spectrum of subjects of interest in the food and beverage industry. A family of solutions reduces the risk of biological and chemical contaminants, respectively, with biocontrol applications against microbial pathogens and spoilers [43–47] and exploiting microbial biochemical activities responsible for the degradation of chemical contaminants [49–51]. Another group of bio-based innovations oriented at ‘label cleaning’, conceive alternatives to chemical preservatives [52–54] and to fortification via the addition of exogenous nutrients [55–57]. Some studies proposed pathways towards enhanced nutrient bioavailability [10,58–60] and improved human health/well-being [61–64] (including microbiome therapies [63–66]), advances of interest to contrast the adverse effects of some negative externalities. Furthermore, the design of several works looking at reducing resource dissipation, saving energy [52,69], valorising foods by-products [52,70,71], foods wastes [72–74], and wastewater [75–77]. Finally, some strategies can preserve microbial diversity associated with food fermentation [78–80].

Table 3. A non-exhaustive list of possible microbial-based solutions as potential mitigating strategies against negative externalities.

Fermentative Processes to Counteract/Prevent Negative Externalities	Ref.
Microbial-based biocontrol of microbial pathogens and spoilers	[43–48]
Microbial-based degradation of chemical contaminants	[49–51]
Bioprotection and alternatives to chemical preservatives	[52–54]
Microbial production of nutrients	[55–57]
Microbes to improve nutrient bioavailability	[10,58–60]
Synbiotic approaches to improve human health and well-being	[61–64]
Microbial biotechnology and microbiome therapies	[65–68]
Microbial resources and strategies to save energy during fermentation	[52,69]
Fermentative valorization of foods by-products	[52,70,71]
Fermentative valorization of foods wastes	[72–74]
Microbial-based valorization of wastewater associated with food systems	[75–77]
Strategies to preserve microbial diversity associated with food fermentation	[78–80]

Some implementations are common to the primary sector and to the studies in food processing. It is the case of protein production that receives interest for both feed and food applications, involving biotechnologies to address a societal or a business need [19,25]. Fermentation and microbial cell factories for producing proteins [81], but also enhancing the nutritional quality of alternative protein sources [82].

It is crucial to underline that the safety of the microbial resources, to avoid any negative side-effects, represents a milestone to assure the sustainability of the solutions reported in Tables 2 and 3 [83,84]. At the same time, the management of microbial resources as ‘commons’, following the standard of microbial biological resource centers (mBRCs), it is of outstanding interest to promote innovation in the field [85,86].

5. Microbes as Mitigating Agents: A Common Denominator of R&D Activities in the Field

This viewpoint article suggests that the challenge of lowering negative externalities would represent a constant part of research and development activities dealing with fermentation and microbial-based biotechnologies in the agri-food sector; a sort of ‘lateral thinking’ [87] with the aims to conciliate product and process innovations with a development respectful of the needs of future generations. In other terms, as the food industry, together with the ‘conventional’ quality of the product (e.g., hygienic, sensory, nutritional, functional) [9], has an increasing ‘side’ focus to sustainable product footprint [88,89], at the same way, food scientists (in the field of microbial-related solutions) could systematically consider the potential as mitigating agents, ‘laterally’ to the innovation proposed. This in consideration that microbial biotechnologies are a driver of innovation but may play a pivotal role in matching sustainability goals and fostering the agri-food system’s resilience. The exploitation of microbial resources is generally considered a knowledge-based reservoir of ‘green’ innovations susceptible to be used in an environmentally, social, and economically conscious manner [1]. However, microbial biotechnologies’ successful implementation needs careful attention since microbial-based solutions are resources of knowledge as created through creative processes and productions and are the primary output of universities and private research centers [90]. Then, microbial biotechnologies are adopted according to the economic conditions in which a company operates as well as to the extent the civil society and consumer accept the use of such biotechnologies [91,92]. Thus, to fully exploit the potential benefits of microbial biotechnologies, there is a need to raise the awareness of their ability to lower the many negative externalities across all the food systems stakeholders (industries, policymakers, academics, and civil society) (Figure 3) [93,94].

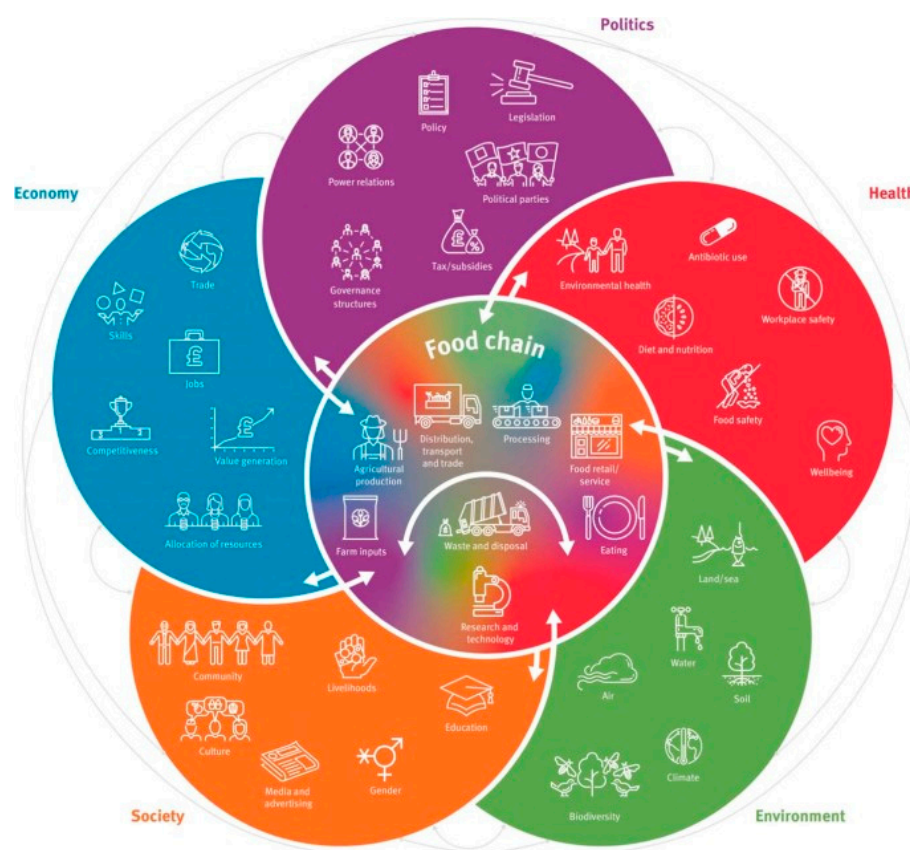


Figure 3. ‘Domains within a sustainable food system framework’; reproduced from Tobin et al. [95].

It is important to consider that microbial biotechnology can contribute to economic progress and employment creation [96]. Also, it is worth saying that microbes and fermented base foods are amply accepted by consumers given the widespread use of fermentation across the many food sectors since ancient time, as well as the general consumers’ acceptance of microbes and related fermentation is rising due to the consumer demand for a more ‘natural’ food that replaces chemical preservatives with natural alternatives (bio-preservatives) [91,97]. These findings contrast the widespread contention that consumers are opposed to the use of biotechnology as they mainly associate biotechnology terms with genetically modified (GM) foods that are, indeed, perceived as an unnatural modification of food and for which consumers ask restrictive policy measures [91,97]. Lastly, related to the microbial biotechnologies and the sustainable economic growth, it is crucial to underline the importance of specific educative programs in the field to favour the people inclination to fair behaviours concerning global challenges such as climate changes and the COVID-19 pandemic [98–101].

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