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Review

Evaluating Biosolutions for Sustainable Food Systems: A Review of Safety, Quality, Regulatory, and Sustainability Considerations Within the European Union

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ABSTRACT

Biosolutions, such as food cultures and fermentates, are emerging alternatives to classical food preservation methods, offering multiple benefits, including food quality and safety enhancement, and waste reduction, with limited sensory and nutritional modification of the product and higher consumer acceptance. This study explores the potential of biosolutions to address critical challenges in sustainable food systems through their application in food production. Evaluation criteria of focus include impacts on food quality and safety, environmental sustainability, and compliance with European regulatory frameworks. The study emphasizes the role of biosolutions in reducing foodborne illnesses, promoting circular economy principles, and building consumer trust. A holistic approach is proposed to support industry stakeholders and policymakers interested in integrating biosolutions into resilient, resource-efficient, and sustainable food systems.

Contents

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Introduction

Fermentation has historically been a cornerstone of food preservation, transforming highly perishable raw materials, such as milk, meat, and vegetables, into safer and more stable products (e.g. yoghurt, cheese, fermented sausage, and sauerkraut). Fermentation relies on complex biological processes that modify the sensory, microbial, and nutritional qualities of raw materials.

Advancements in technology have shifted food preservation toward maintaining food's original sensory and nutritional properties. Widely used methods, such as modified atmosphere packaging, "synthetic" preservatives, and advanced resource-intensive, plastic-based storage systems, enable food producers to better control the microbiome without significantly transforming raw materials. However, these approaches often raise concerns about their environmental impact and consumer acceptance.

This paper introduces an approach to food preservation based on biosolutions, here referring specifically to food cultures and fermentates, both closely tied to fermentation. These biotechnology solutions aim to replicate the benefits of traditional and modern preservation methods without the drawbacks of resource-intensive packaging, and synthetic chemicals, while limiting the transformation of the food products. By leveraging natural biological processes like fermentation, biosolutions are claimed to offer sustainable solutions and increase resource efficiency (Capozzi et al., 2021; Cocolin, 2024). They also may support the "clean-label" or "label-friendly" trend by promoting simple, recognizable ingredients and reducing additives (Probst et al., 2015). Additionally, these biosolutions improve food safety and enhance shelf life by maintaining sensory qualities and nutritional value under appropriate storage conditions (Lisboa et al., 2024; Mathur et al., 2020; Probst et al., 2015; Reuben & Torres, 2024). They are increasingly applied across diverse food matrices (e.g. Choi et al., 2023; Fischer & Titgemeyer, 2023), mitigating spoilage and delaying the growth of harmful microorganisms, such as *Listeria monocytogenes* (e.g. Heir et al., 2019; Ibrahim et al., 2021). Research initiatives, e.g. the EU-funded Microorc (2025) and Foodguard (2025) projects, further advance microbiome-based innovations to promote sustainable food systems.

This paper examines the holistic selection strategy, mode of action, safety, and European regulatory considerations of food cultures and fermentates, addressing the key criteria for their successful implementation in food systems. Ultimately, it aims to facilitate more informed decision-making by industry stakeholders, policymakers, and regulatory authorities.

Evidence of efficacy and limitations

There is abundant literature on the efficacy of biosolutions in food applications including bread, fermented milk, cheese, salami, cooked ham, smoked salmon, and fresh vegetables (e.g. Choi et al., 2023; Heir et al., 2019; Ibrahim et al., 2021, Borges et al., 2022, Fischer & Titgemeyer, 2023). Reported limitations include the complexity of the food matrix on biosolution efficacy, the stability of biosolutions under different environmental factors, the application mode, and potential negative effects on the nutritional and organoleptic properties of foods.

The evaluation criteria presented in this study include regulatory aspects, microbial effects, food safety and quality, application challenges, sustainability, and consumer-focused metrics (Table 1).

Categories of biosolutions. Food cultures are defined by the European Food and Fermentation Association (EFFCA) as "safe live bacteria, yeasts, or filamentous fungi (molds) used in food production, which themselves constitute food ingredients. Food cultures preparations are formulations, consisting of concentrates (>10E+8 CFU/g or mL of bacteria and yeasts; >10E+7 CFU/g for filamentous fungi) of one or more live and active microbial strains of one or more microbial species. Food cultures also include metabolites and media components carried over from the fermentation and components (e.g., carbohydrates, organic acids, minerals, vitamins) which are necessary for their survival, storage and to facilitate their application in the food" (EFFCA, 2023).

Fermentates are formulations typically composed of the liquid part (supernatants) of fermented bacteria (mostly lactic acid bacteria), yeasts, or moulds and the metabolites and bioactive compounds produced during fermentation. In commercial fermentates, cells are usually inactivated after fermentation and metabolite production (Mathur et al., 2020). These products are commonly concentrated and dried into powders by evaporation, freeze- or spray drying (Figueroa et al., 2024). Examples include "buffered vinegars", "cultured dextrose", "cultured sugar", "fermented sugars", "fermented wheat flour", "cultured milk", or "cultured whey". Their exact composition can be difficult to obtain as they often contain mixtures of organic acid salts but also bacteriocins and other metabolites.

Mode of action. Food cultures and fermentates may achieve their effects through a synergistic combination of microbiological competition and/or the production of multiple antimicrobial metabolites (e.g. bacteriocins, organic acids), especially when live microorganisms are present.

Microbiological competition includes competition for substrates necessary for growth and metabolism (Ghoul & Mitri, 2016) and space. Outcomes are therefore dependent on the food matrix and the individual demand and nutrient consumption rate of microorganisms. Competition for space arises from microbial biomass expansion, where motility of some bacteria can give them an additional advantage to compete for space and to move faster toward substrates (Gude et al., 2020).

The production of antimicrobial metabolites is another key mode of action. Food cultures and fermentates may produce or contain bioactive compounds such as bacteriocins and organic acids, which can

Table 1
Main parameters and criteria to consider for a holistic selection of biosolutions for food applications

Law, standards, guidelines, and other specifications	EU & national regulations on food additives, novel food, labeling requirements, and food safety Standards of identity of food products, positive list of ingredients Microbial specifications on lactic acid bacteria or mesophilic aerobic count
Efficacy data	Impact on selected pathogenic microorganisms' growth Impact on the natural microbial ecosystem (composition and growth of specific species/genus)
Technical feasibility/ application method	Need for investment Need for modification of the process (application method)/recipe (heat sensitivity, etc.) Need to change the microbial criteria used as hygiene indicators Batch size of the biosolution (g or mL/kg) vs. food batch size (kg) Need for new (critical) control points Storage condition/shelf life of the biosolution
Sensory	Impact on taste, smell, texture, and color over the shelf life
Consumer requirements	Halal/kosher Allergen status Organic Vegetarian/vegan
Economical aspect	Cost in use Impact on productivity Impact on costs of food waste and recalls
Life cycle sustainability	Resource efficiency Food waste reduction Nutritional value preservation

inhibit the growth of spoilage organisms and pathogens (Reuben & Torres, 2024). Databases like DRAMP (Data repository of antimicrobial peptides) catalogue over 431 bacteriocins, facilitating research and applications on them (Ma et al., 2024).

Lactic acid bacteria (LAB) used as food cultures produce multiple bacteriocins which vary widely in size and structure, and in stability under different pH and temperature conditions (O'Sullivan et al., 2002; Reuben & Torres, 2024). Strains of *Lactilactobacillus*, *Lactococcus*, *Carnobacterium*, *Enterococcus,* and *Pediococcus* are known to frequently harbor genes encoding for bacteriocin production. Therefore, a careful selection of appropriate food cultures with bacteriocins that effectively target-specific microbes under food storage conditions and account for matrix interactions is key.

The effectiveness of bacteriocins in controlling spoilage and pathogenic microorganisms has been well-documented across various food applications (Borges et al., 2022). Their mechanisms of action are extremely diverse (Sugrue et al., 2024). Many bacteriocins form membrane pores in the cell of target bacteria, leading to dissipation of the proton motive force, leakage of essential ions and small molecules, and ultimately cell death. Others can penetrate the membrane and interfere with essential cellular processes like cell wall biosynthesis, leading to lethal effect. The risk of resistance development remains a concern (Kramer et al., 2006; Sun et al., 2009; Bastos et al, 2015; Kjos et al., 2011; Kumariya et al., 2019), making identification of novel bacteriocins a research priority (Draper et al., 2015; Koniuchovaitė et al., 2023).

Organic acids, the main constituents of fermentates produced by food cultures, decrease the pH of their environment and create unfavorable conditions for the survival and growth of microorganisms. Lactic and acetic acids are the primary acids produced by LAB, while some strains and other species, e.g., *Propionibacterium,* can also produce propionic, malic, succinic, butyric, and formic acids (Punia Bangar et al., 2022; Piwowarek et al., 2017). The main antimicrobial effects of organic acids are bacteriostatic, caused by the undissociated acid molecules that penetrate microbial membranes, acidify the cytoplasm, and disrupt critical metabolic pathways. However, over-acidification can impair taste and texture, requiring balance between efficacy and sensory quality. Rapid sensory profiling helps assess this trade-off (Delarue & Lawlor, 2023).

LAB also produce other antimicrobial compounds, including hydrogen peroxide, diacetyl, and CO_2. Hydrogen peroxide can cause oxidative stress in several bacterial targets, disrupting their cellular integrity and metabolic processes. Diacetyl, a byproduct of certain fermentation processes, can inhibit the growth of bacteria, particularly Gram-negative strains and yeast, by interfering with enzymatic activity and cellular functions. As for organic acids, diacetyl may impact flavor at high concentrations. CO_2, produced by heterofermentative LAB, contributes to an anaerobic environment that inhibits the growth of aerobic spoilage microorganisms and suppresses competing microbiota by lowering intracellular pH, altering membrane fluidity, and disrupting metabolic pathways and DNA replication (Esmaeilian et al., 2021).

Like organic acids, the production of these antimicrobial substances can also negatively affect the sensory characteristics of foods, requiring a careful balance between antimicrobial efficacy and desirable taste and aroma.

Safety and regulatory aspects in the EU

Accurate classification of biosolutions is critical, as it determines the regulatory framework applicable to labeling, premarket approval, and enforcement (Sakihara, 2018a, 2018b). Classification depends on various horizontal EU regulations such as Regulation (EC) No. 1333/2008 on food additives, published by the European Parliament and Council (2008a) and Regulation (EU) No. 1169/2011 on food information (European Parliament and Council, 2011).

One of the biggest challenges in classifying biosolutions is that their uses often overlap with definitions of multiple regulatory categories. As noted by Herody et al. (2025) and De Dea Lindner et al. (2024), the application of food cultures often blurs the distinctions between food ingredients, food additives, and novel food products, resulting in their classification as 'borderline ingredients'. The minutes from the Standing Committee on Plants, Animals, Food, and Feed (SCOPAFF) provide further guidance on the status of borderline ingredients. For example, buffered vinegar (European Commission, 2020) and certain rice products (European European Commission, 2021) have been reclassified as food additives under specific conditions.

According to Article 2.2 (f) of Regulation (EU) No. 1169/2011, a food ingredient is "*any substance or product, including flavorings, food additives, and food enzymes, as well as any constituent of a compound ingredient, used in the manufacture or preparation of food and still present in the finished product, even if altered; residues shall not be considered as 'ingredients*" (European Parliament and Council, 2011). Furthermore, according to Article 14.1 of the General Food Law, "*Food shall not be placed on the market if it is unsafe*" (European Parliament and Council, 2002). Thus, it is the responsibility of the food business operators to ensure the safety of the food before it is placed on the market.

When biosolutions are used in conventional ways, for example as cultures added to initiate fermentation, they do not require premarket approval or authorization. This applies particularly to food cultures, which are deliberately added to food to promote fermentation *via* their metabolic activity or competitive exclusion and are naturally consumed in fermented foods (Herody et al., 2025). If a biosolution is used specifically for a technological function, such as microbial inhibition, and is not typically consumed alone or used as a base food ingredient, it may meet the definition of a food additive under Regulation 1333/2008, causing stricter requirements (European Parliament and Council, 2008a; Herody et al., 2025). There is an ongoing debate among Member States regarding the classification of food cultures used for technological purposes. The regulatory complexities highlighted by De Dea Lindner et al. (2024) emphasize the need for international harmonization and a clear consensus on defining and categorizing these biosolutions, facilitating their integration into sustainable food systems.

The footnotes of Regulation 1333/2008 clarify that substances produced *in situ* during fermentation are not regarded as additives. This means that if antimicrobial effects arise naturally from the fermentation process without added concentration or extraction, the substance remains classified as part of the ingredient and not as a separate additive (European Parliament and Council, 2008a).

The assessment process encompasses several key components, including Qualified Presumption of Safety (QPS) approach, developed by the Scientific Committee of EFSA (European Food Safety Authority) in 2007 to provide a generic concept to prioritize and harmonize the risk assessment of microorganisms to be added to food and feed. The QPS list should not be viewed as a positive list, but rather as a safety assessment procedure that evaluates the safety of specific microorganisms based on existing knowledge and scientific evidence. Inclusion of a species on the QPS list provides a strong foundation that does not raise safety concerns. Absence from the list does not imply that a microorganism is unsafe but results from factors such as the absence of an EFSA evaluation or insufficient data for assessment.

As a decision aid, the classification tree provided in Figure 1 can help determine whether a biosolution should be regulated as a food ingredient or a food additive, helping food business operators ensure correct and consistent application of EU legislation.

Novel food regulation. When biosolutions are classified as regulated products (e.g. novel food or additive), they require authorization and safety assessment in line with Regulation (EC) No. 1331/2008 for food improvement agents, such as enzymes, flavorings, and additives, and Regulation 2017/2469 for novel foods (European Parliament and Council, 2008b; European Commission, 2017). To support applicants,

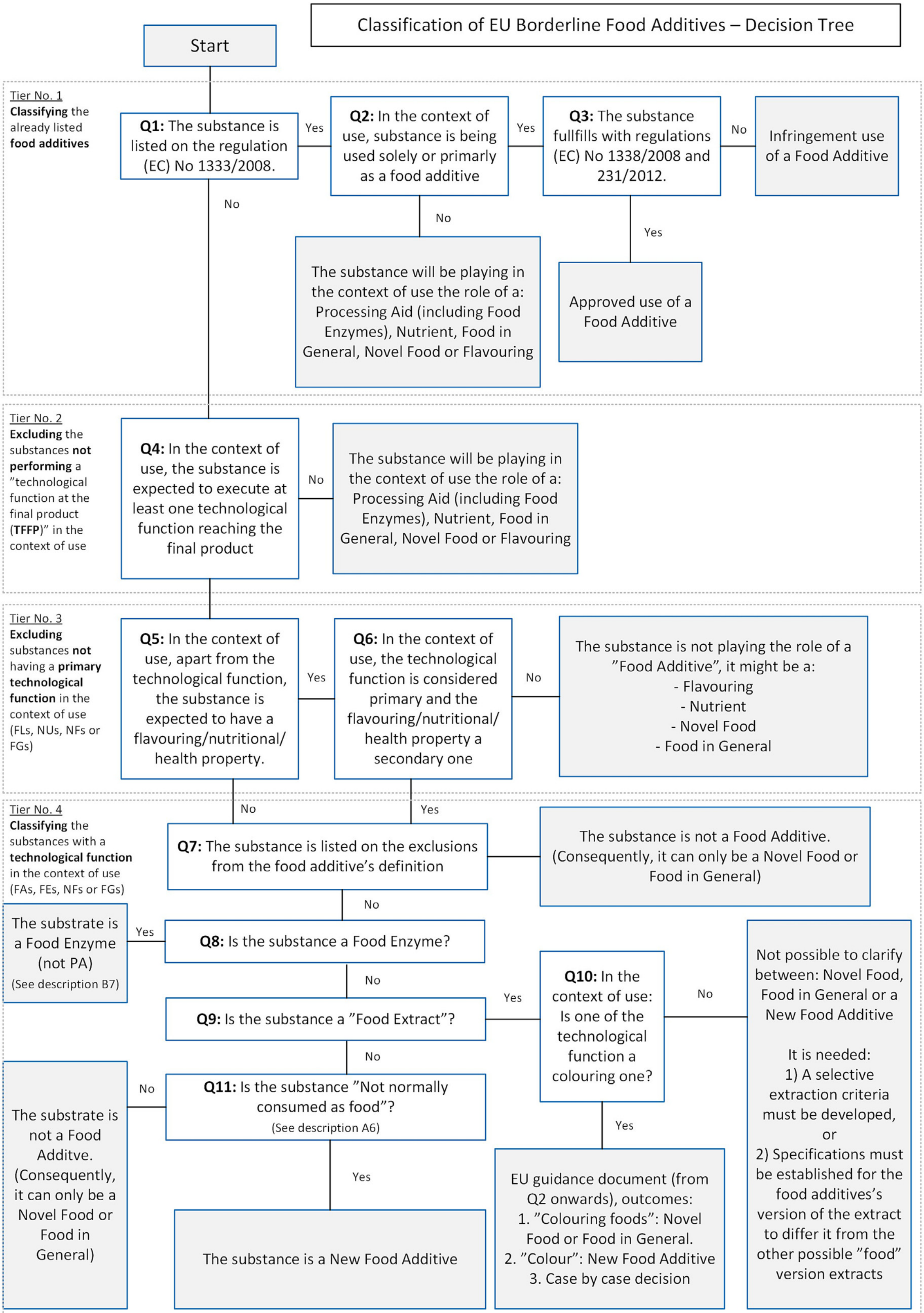

Figure 1. Decision tree of EU classification of Food ingredients with technological properties (Sakihara, 2018b).

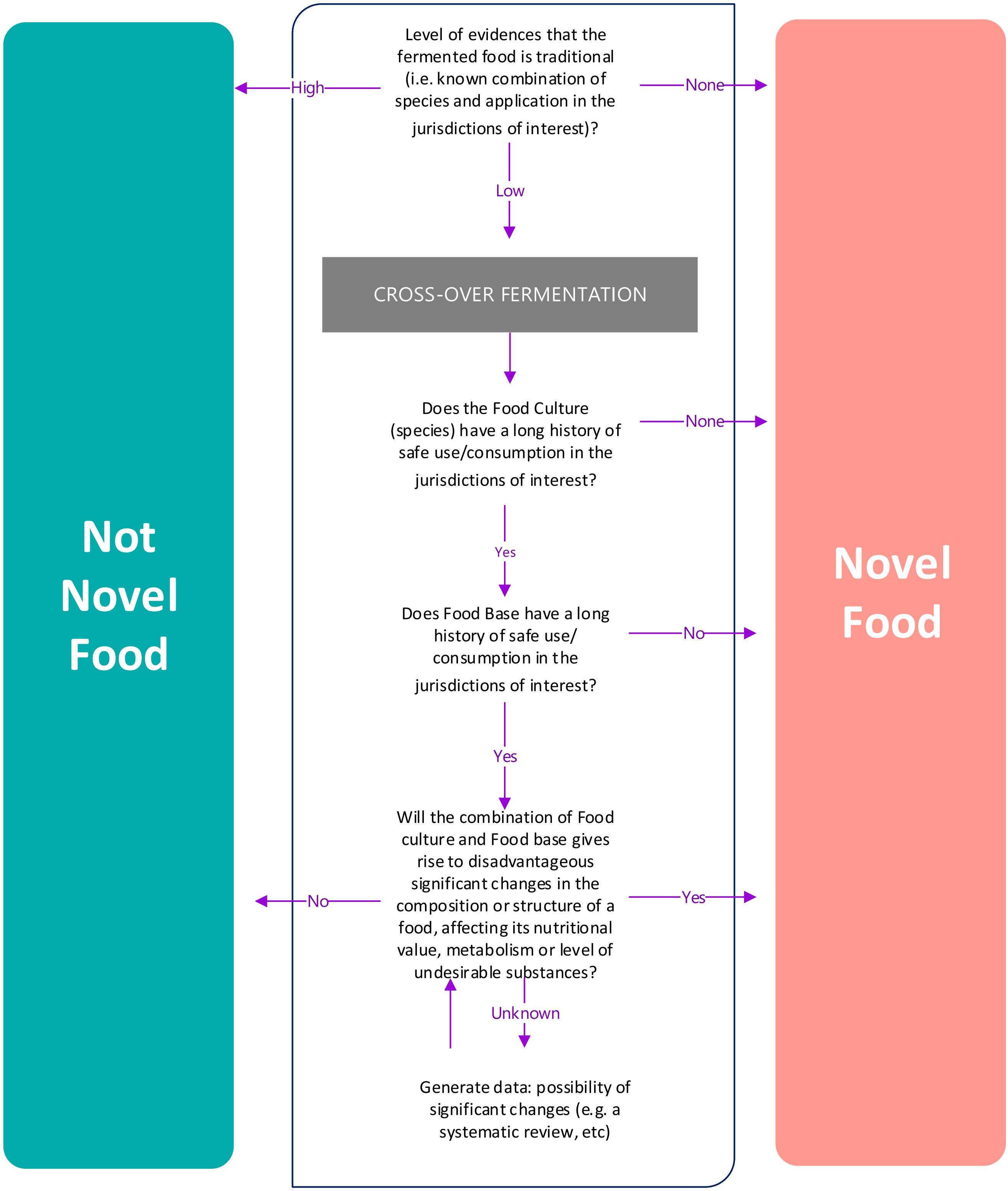

Figure 2. Example of a decision tree for assessment of the "novel food" status of fermented foods (created by Novonesis, internal document). Cross-over fermentation is defined by Bourdichon et al. (2022).

EFSA provides detailed scientific guidance on the preparation and submission of dossiers, including the nature and extent of the data required for risk assessment (Turck et al., 2024).

'Novel foods' are foods or food ingredients without a history of significant consumption in the EU before 15th May 1997, or those produced using new processes which result in significant changes to their composition or structure, affecting nutritional value, metabolism, or levels of undesirable substances.

Although fermentation is a traditional production process, innovative combinations of microorganisms and food bases can induce significant changes to the food matrix. Fermentation often enhances the nutritional value of foods by enriching them with microbial protein, amino acids, and vitamins absent from the original food source. Such natural conversions are not considered novel. Novel food status is more likely to apply when a specific compound is harvested, concentrated, or further purified.

The European Commission has recognized the ambiguity surrounding what constitutes a "significant change" and has proposed issuing guidelines to clarify this point. Until then, food business operators are advised to follow the consultation procedure under Article 4 (European Parliament and Council, 2015).

To evaluate the novel food status of fermented foods, Novonesis developed the decision tree shown in Figure 2 for internal use. With modifications, this decision tree could also be applied to assess the production of fermentates.

To support regulatory assessments of microbial food cultures and their applications, the EFFCA and the International Dairy Federation (IDF) compiled an inventory of food cultures with documented use prior to 1997. First published in 2002 (Bourdichon et al., 2021) and updated in 2012, 2018, and 2021 (Bourdichon et al., 2012, 2018, 2021), it has expanded from 113 to 325 species used in a wide range of food matrices. This valuable resource aids in determining historical use and ensuring compliance with the Novel Food Regulation.

Labeling requirements. The regulatory classification of biosolutions will affect the information provided on labels of final food products, with ingredients and additives required to be listed according to Article 36 of Regulation (EU) No. 1169/2011. Voluntary labels, such as halal, kosher, vegan, vegetarian, and organic, can also be included, if they are truthful, not misleading, and supported by scientific data (European Parliament and Council, 2011).

The clean label trend has emerged as a dominant force shaping food labeling practices, driven by consumer demand for natural, minimally processed foods with "short ingredients list". Despite its widespread influence, "clean label" lacks a formal or universally accepted definition in EU regulations (Asioli et al., 2017), leading to varied interpretations and practices across Member States and industries. For example, the Netherlands and Belgium have provided guidelines addressing the clean label trend, emphasizing the use of ingredients with technological functions as substitutes for food additives (e.g., fermented vegetable broth substituting nitrate, spinach extract substituting high nitrate levels used in sausages, etc.). Authorities warn that these practices may mislead consumers if the functional roles of these ingredients are not clearly disclosed. Consequently, ingredients used for technological purposes must comply with food additive legislation to ensure transparency and regulatory compliance (Cegiełka & Tambor, 2020; European Parliament and Council, 2011).

This trend reflects a broader shift in consumer behavior, with individuals increasingly seeking foods perceived as healthier, simpler, and more sustainable. Claims like "free from artificial additives," "natural," and "organic" are significant motivators, even in the absence of strict regulatory definitions (Asioli et al., 2017). As a result, biosolutions are increasingly used as natural or label-friendly solutions aligned with these preferences.

Sustainable food labeling. The EU is developing a new framework for sustainable food labeling under the Farm to Fork Strategy, aiming to harmonize sustainability labeling by integrating environmental, social, and economic dimensions across the food value chain to guide more sustainable choices (European Commission, 2023).

Although biosolutions, such as fermentates and food cultures, are not currently addressed, their alignment with clean label principles and sustainability objectives makes them strong candidates for future integration. Biosolutions provide consumer-friendly and environmentally sustainable alternatives to additives, contributing to food preservation, waste reduction, and circular economy goals (Alexandre et al., 2023; Elsser-Gravesen & Elsser-Gravesen, 2013; Kovalchuk, 2021).

Recent research on sustainability claims and labels highlights the increasing consumer demand for transparent and sustainable food labeling across the EU, especially for health, environmental impact, and naturalness, which align with both the simple label movement and broader sustainability goals (Nes et al., 2024). The European Biosolutions Coalition, established in October 2023, advocates for the integration of biosolutions into EU policies to enhance sustainability, resilience, and communicate benefits more clearly.

Framework for evaluating quality and safety

A holistic evaluation of biosolutions requires an integrated approach to ensure they meet safety, regulatory, and environmental standards, while maintaining food quality and addressing consumer expectations. This framework outlines the key components of efficacy testing, sensory evaluation, and process optimization to achieve these goals.

Evaluating the efficacy of biosolutions involves systematic testing to identify and mitigate microbial hazards and spoilage organisms that can contaminate food. This evaluation aligns with the principles of "Hazard Analysis and Critical Control Points" (HACCP) and Good Manufacturing Practices (GMP) outlined in Regulation (EC) No. 852/2004 on the hygiene of foodstuffs (European Parliament and Council, 2004).

The first step is to identify relevant microbial hazards and spoilage organisms. It includes:

- Considering potential contaminants: Reviewing outbreak data and identifying pathogens and spoilage organisms that may contaminate and grow in the target food matrix.
- Consulting historical data: Reviewing outbreak and contamination data for similar food products to anticipate microbial risks.
- Understanding microbial behavior: Evaluating the conditions under which these microorganisms grow, survive, or produce toxins or off-odors (e.g., temperature, pH, water activity).

Once the relevant hazards are identified, biosolutions must be tested whether they can effectively reduce or inhibit the growth of identified hazards and spoilage organisms during storage. This step involves challenge tests and microbial shelf life studies in food with and without biosolution.

Challenge tests are used to investigate the ability of an artificially inoculated microorganism of concern to grow or survive in a product under foreseeable storage conditions. They are essential when natural contamination is sporadic or rare. Harmonized testing methodologies have been established. The European Union Reference Laboratory has published a technical guidance document for conducting shelf life studies on *L. monocytogenes* in ready-to-eat (RTE) foods (European Union Reference Laboratory for L. monocytogenes, 2021). An international and more general standard has been developed (ISO 20976-1:2019, 2019) for vegetative and spore-forming bacteria.

Microbial shelf life studies are used to determine the durability of products under storage, primarily regarding the expected effect of microbial growth on the sensory properties. In the context of food preservation, it is important to determine the effect of a biosolution not only on pathogenic microorganisms but also on larger bacterial communities naturally occurring in most of the nonappetized food. There is no single method for establishing the shelf life of food products, as many different factors can affect product quality. There are numerous guidelines, standards, and legislative frameworks that provide a comprehensive structure for determining the shelf life of food products. In most of them, it is recommended to quantify microbial ecosystems by selective counts using ISO methods when available and to also study other nonmicrobial indicators such as pH, water activity, and biogenic amines. The use of q-PCR, metabarcoding, and other metagenomes widely applied in a scientific context is not yet democratized at an industry scale. As an example, the Food Safety

Authority of Ireland (FSAI) has issued Guidance Note No. 18, which provides detailed guidance on the validation of product shelf life (FSAI, 2022). This guidance extends the above approaches and provides detailed methodologies for establishing and validating shelf life in accordance with regulatory requirements. Industry-specific guidance, such as that provided by the Food and Drink Federation (FDF), emphasizes the importance of understanding the factors that affect shelf life, including raw materials, packaging, and storage conditions (FDF, 2017), helping food business operators to assign appropriate use-by dates to their products and to validate shelf life.

Sensory quality assessment. Evaluating the impact of biosolutions on the sensory quality of food is essential for their selection and validation. While food microbial and biochemical criteria are important, they do not always correlate with organoleptic characteristics. Therefore, evaluating sensory properties is necessary to ensure that biosolutions meet consumer expectations and maintain market viability, supporting their wider adoption.

Sensory analysis involves evaluating the visual aspect, color, odor, taste, and texture of a product. Sensory profiling and discrimination tests consist of precisely measuring or comparing the sensory characteristics. They are performed by trained assessors under controlled conditions (cabin, box, temperature, light) specified in ISO 8589:2007 (ISO, 2007). ISO 13299:2016 (ISO, 2016) proposes general guidance for establishing a sensory profile. Hedonic tests are used to evaluate consumer appreciation (acceptability, preference) (ISO, 2014). They are performed by untrained people, in the food factory or at home. There are no regulatory criteria for these tests, and the results are subjected to the judgment of the food business operator. To ensure reliable results, special attention must be paid to sample preparation to reduce product variability (same sampling area, size, temperature, presentation). Delarue and Lawlor (2023) further highlight the importance of designing sensory tests that minimize variability while ensuring the reliability of the results, which is critical when validating biosolutions intended for wide-scale market adoption.

Process optimization. For optimal efficacy, biosolutions must be properly distributed within or on the food product. Food cultures require application before any lethal treatment (e.g., thermal processing), while fermentates can generally be added beforehand, as most bacteriocins and organic acids remain effective after heating. Various application methods are available, as highlighted by Fischer and Titgemeyer (2023), who discuss the transition of food cultures from science to market. Such as:

- Direct addition into foods, either simultaneously with other ingredients such as spices (e.g., minced products), or through injection (e.g., cold-smoked salmon or cured whole meat pieces), is a widely used method that can be implemented into the existing production process without costly investments.
- Dipping, which involves immersing food products in a solution containing the biosolution. This technique ensures thorough coating of the product´s surface but does not always allow penetration of the antimicrobial agent into the core of the food matrix. If slicing or dicing occurs after dipping, the newly exposed surfaces will not be protected. Cross-contamination risks and ensuring consistent concentration on each item are key challenges, making it difficult to establish this step as a reliable critical control point in the manufacturing process.
- Spraying, suitable for foods such as salads, bread, hotdog sausages, and sliced cold smoked salmon, ensures even surface coverage, but requires an investment in a spraying device equipped with appropriate nozzles to ensure precise control of the flow.

Whatever the technique used to apply biosolutions, it is essential to perform regular analyses to ensure the concentration of biosolution on or within the food is sufficient to achieve its intended antimicrobial effect.

Hygiene standards and infrastructure for biosolution integration. When applying biosolutions, particularly food cultures at high levels (10^6–10^7 CFU/g or higher), traditional hygiene indicators such as Total Viable Count (TVC) or LAB counts may no longer be applied, since it may be impossible to differentiate between spoilage organisms and biosolutions themselves using these methods. Consequently, food producers must establish new hygiene criteria that allow for more accurate monitoring of food quality and spoilage. Alternative methods can include the calculation of the ratio between TVC and LAB, or using specific spoilage organism counts, which focus on identifying and measuring only the microorganisms that cause spoilage, excluding the beneficial bacteria from biosolutions. Additionally, chemical indicators such as biogenic amines or volatile compounds can signal microbial activity, while pH changes and alterations in texture provide further evidence of spoilage or degradation.

Integrating biosolutions also requires capital expenditure (CapEx) in application equipment – such as spraying devices, immersion units, or injection systems, depending on the chosen method of application. Application methods must balance efficacy with economic feasibility.

Proper storage conditions are another important factor. Fermentates are typically shelf stable for several months under ambient conditions, while food cultures usually require cold storage. Freeze-dried food cultures often need storage temperatures at −18 °C for long-term preservation, lasting at least over one year (often 18 months), while they can be stored at refrigerated temperatures for shorter durations, typically a few weeks. Pellets of food cultures are stable for more than a year at −55 °C. Liquid frozen cultures usually need storage at −18 °C (Celik and O'Sullivan, 2013; Thunell, 1996).

Life cycle sustainability

Certain biosolutions have been shown to extend shelf life and improve microbial stability in specific food products, including meat, dairy products, or seafood (Desai et al., 2014, Figueroa et al., 2024, Zhang et al., 2018). Biosolutions, by improving food safety, have the potential to contribute to all three dimensions of sustainability: environmental, social, and economic. Recent advancements in nutritional Life Cycle Assessment (nLCA) demonstrate the feasibility of integrating environmental and nutritional impacts into a more holistic evaluation approach and the opportunity for developing an Integrated Sustainability Index (McAuliffe et al., 2024). Such an index could serve as a practical tool for food producers and policymakers, enabling them to assess and benchmark the overall sustainability performance of food products. To fully capture the complexity of sustainability impacts, a multicriteria assessment (MCA) approach is essential (Lindfors, 2021), allowing to quantify both environmental and nutritional trade-offs in food system interventions, highlighting its value in supporting holistic food policy decisions. To ensure rigorous assessment, it is necessary to combine functional shelf-life and safety data from controlled food trials with primary inventory data on biosolution production and use.

Environmental criteria. It is anticipated that when evaluating the environmental footprint of food products using a cradle-to-cradle life cycle approach, as recommended by PEF (European Commission, Joint Research Centre, 2018), and a functional unit based on the final product (e.g. 1 kg of consumed food), the direct environmental contribution of adding biosolution is minor compared to the total environmental footprint of the food product, similar to conventional preservatives. Nonetheless, Boye and Arcand (2012) identified biopreservation as a promising green processing strategy for enhancing sustainability in food systems, though benefits depend on the production process, underscoring the need for case-specific assessment of biosolutions within a life cycle framework.

Although biosolutions are not currently modelled in most existing databases such as Ecoinvent or Agribalyse, several recent studies attempted to define their environmental profile. Figueroa et al. (2024) noted that 'the most common antimicrobial agents used in foods, such as benzoates, sorbates, and propionates, are produced with significant environmental impacts,' indicating the need for alternatives. Some synthetic preservatives, like acetic acid, may be produced from methanol, which typically originates from fossil sources (Mushfiq, 2022). Muthuvelu et al. (2023) reviewed the environmental and functional attributes of microbial biosolutions and highlighted their potential to reduce reliance on synthetic preservatives. Fermentates production via microbial fermentation allows for flexibility in substrate use, enabling the valorization of food industry side streams such as whey or vegetable peels, supporting circular economy principles (Alexandre et al., 2023; Ricci et al., 2021). Most studies to date have focused on fermentates derived from lactic acid bacteria, but microbial groups like Bacillus or Propionibacterium show promise allowing for similar applications when valorizing food industry side streams (Sadh et al., 2018). This practice reduces waste and repurposes potential by-products into valuable preservation agents, significantly lowering the environmental footprints (Ibrahim et al., 2021; Teigiserova et al., 2021; Bhowmik et al., 2024).

Indirect effects, particularly those linked to clean-label shelf-life extension, can be environmentally significant. Food waste remains a major global concern with substantial environmental and socio-economic impacts, including embedded greenhouse gas emissions, land degradation, and lost economic value (FAO, 2013). Fermentates and food cultures have demonstrated the ability to inhibit spoilage organisms and foodborne pathogens, such as *Listeria monocytogenes,* in various food matrices (Hartmann et al., 2011). This improves microbial stability and prolongs freshness, thereby reducing waste both at the retail level (e.g., unsold expired inventory) and among consumers (Reyes et al., 2024). The scientific literature lacks robust data on the direct correlation between shelf life extension and food waste reduction, but Reyes et al. (2024) estimated that a 10-day extension in chicken shelf life reduced waste by 6–7%, decreased CO_2 emissions by 457–567 kg, and saved 656,571–814,149 L of water per 1,000 kg of product. To capture these environmental gains, it is essential to define parameters and quantify the link between product stability and waste reduction. This aligns with calls from Teigiserova et al. (2021) and Brancoli et al. (2020) for life cycle approaches that integrate food loss metrics in the evaluation of environmental performance.

Socio-economic criteria. Unlike certain synthetic preservatives, which have been shown to degrade sensitive nutrients like thiamine and are associated with potential health effects (Bensid et al., 2020), biosolutions have the potential to maintain the nutritional integrity of foods throughout storage and distribution. For example, fermentates obtained from LAB can retain bioactive compounds and vitamins such as folate and riboflavin (Figueroa et al., 2024). Similarly, food cultures used in fermented dairy and plant-based products demonstrated an ability to stabilize essential fatty and amino acids, minimizing nutrient loss. In the case of fresh fruit applications, food cultures have been associated with slower degradation of antioxidants such as ascorbic acid, which are prone to loss (Lisboa et al., 2024).

The link between preserving nutritional value and socio-economic benefits lies in providing consumers with healthier, high-quality foods while minimizing nutrient loss during storage and transport. This alignment supports consumer preferences for natural, minimally processed foods and contributes to broader public health objectives, reducing reliance on excessive salt or sugar often used in conventional preservation (Ibrahim et al., 2021).

Consumer acceptance and sensory qualities. Biosolutions should not negatively affect consumer acceptance by changing the standard of identity and characteristics of the product (FDA, 2025). This is quite challenging as many fermentates and food culture can acidify food and be detected by sensory panellists in the few days following inoculation, although their beneficial effect to reduce spoilage is demonstrated (Macé et al., 2023). If carefully selected, they can enhance microbial and sensory properties, making foods more appealing to consumers (Bhowmik et al., 2024; Elsser-Gravesen & Elsser-Gravesen, 2013; Heir et al., 2019; Heir et al., 2022). For instance, the use of fermentates in beverages and fresh produce has demonstrated improved flavor profiles and product integrity during extended storage (Alexandre et al., 2023). This builds consumer trust in food products and meets the demand for natural options (Chang & Chen, 2022; Ciobanu et al., 2024; Innova Market Insights, 2023; Latoch et al., 2023; Rieger et al., 2016).

Public health and safety. Biosolutions have demonstrated the ability to mitigate foodborne illness by targeting pathogens such as *L. monocytogenes*, *Salmonella* spp., and *Escherichia coli* (Bensid et al., 2020; Ibrahim et al., 2021; Silva et al., 2024), reducing the risk of foodborne outbreaks and illness cases and associated costs. This can be evaluated through Disability-Adjusted Life Years (DALYs), a metric combining years of life lost due to premature mortality and years lived with disability (Murray & Lopez, 1996). For example, a 50% reduction in the incidence of *L. monocytogenes* could halve the associated DALYs, improving public health but also reducing healthcare costs (Bhowmik et al., 2024). Foodborne diseases pose a significant global health and economic challenge. According to the World Health Organization (WHO), foodborne illnesses affect approximately six hundred million people annually, leading to 420,000 deaths worldwide. In the European Union (EU), twenty-three million cases of foodborne illnesses occur every year, resulting in approximately 5,000 deaths (WHO, 2015).

Reducing the occurrence of foodborne illnesses translates into healthcare cost savings due to fewer hospitalizations, reduced medication needs, and minimized loss of productivity (Figueroa et al., 2024). This includes lower expenses for hospitalization, medication, and loss of productivity. These benefits can be quantified by applying LCA, including changes in greenhouse gas emissions, resource use, and health burdens, potentially supporting more sustainable food systems (Okoye et al., 2022).

Moreover, biosolutions reduce the risk of food recalls, which impose direct financial burdens, such as logistics and product replacement, but also lead to long-term reputational damage for brands (Thomsen & McKenzie, 2001; Pozo & Schroeder, 2016; Lee & Boys, 2018; Kong et al., 2019). As the food industry increasingly adopts biosolutions, the dual benefits of waste reduction and recall prevention present a case for their integration into production systems.

Conclusions

Biosolutions represent potential solutions to reduce global sustainability challenges and food waste and align with legislative frameworks such as the EU Farm to Fork Strategy. By leveraging natural fermentation and biological processes, they offer safer, efficient, and environmentally friendly alternatives to traditional food preservation methods.

This study highlights the need for a holistic framework of evaluation criteria, including quality, safety, sustainability, and consumer-focused metrics, to guide the effective implementation of biosolutions in food systems. Future research should prioritize the operationalization of this framework across diverse food matrices and production processes.

A harmonized regulatory classification is crucial to ensure consistency and transparency across EU markets. Responsive policies must foster, rather than hinder, the development of innovative biosolutions in the food system. Integrating biosolutions into circular economy models, such as utilizing side streams and reducing resource dependency, further aligns their application with sustainability principles.

Developing integrated metrics for sustainability, such as an Integrated Sustainability Index, can provide insights into the environmental, health, and economic benefits of biosolutions. Such a tool would support informed decision-making for policymakers and food producers alike. Expanding the application scope of biosolutions across diverse food matrices and production processes would enhance their value proposition.

Consumer and industry education remains vital for market acceptance. Highlighting the safety, natural origin, and waste-reducing potential of biosolutions can encourage widespread adoption. As interdisciplinary initiatives like the MICROORC and the FOODGUARD projects continue to explore advanced applications, such as dynamic shelf life labeling and foodborne illness reduction, the future of biosolutions becomes increasingly promising.

Future research should address the scalability and cost-effectiveness of biosolutions for industrial use, their contribution to long-term EU sustainability targets, and the development of innovative formulations that balance "clean label" principles with measurable sustainability impacts.

While the present review focuses on the European context, which reflects the geographic scope and affiliations of the authors, extending the analysis to include regulatory, market, and microbial dynamics in other regions, such as Asia, North America, Africa, and Oceania, would provide a more complete understanding of the global relevance and transferability of biosolutions (Fischer & Titgemeyer, 2023).

During the preparation of this work, the author(s) utilized ChatGPT to assist with improving readability and language. The author(s) subsequently reviewed and edited the content as necessary and took full responsibility for the final content of the publication.

CRediT authorship contribution statement

Marianne Thomsen: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Françoise Leroi:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Validation, Writing – review & editing, Writing – original draft. **Delphine Passerini:** Conceptualization, Funding acquisition, Investigation, Resources, Validation, Writing – review & editing, Writing – original draft. **Milena Siemiatkowska:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Tirzania Sopacua:** Conceptualization, Investigation, Resources, Validation, Writing – review & editing, Writing – original draft. **Kristina Andersson:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Conceptualization. **Paula Teixeira:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Fatima Poças:** Writing – review & editing. **Even Heir:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Solveig Langsrud:** Writing – review & editing. **Véronique Zuliani:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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