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Viewpoint

Emerging evidence on the potential of PTR-MS as rapid, direct and high-sensitivity sensors to promote innovation in the fermented beverages sector

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Summary In food technology, the term 'fermentation' encompasses a spectrum of microbial-driven bioprocesses that preserve and improve the quality of raw materials, transforming them into new fermented products with minimal resource consumption. Furthermore, fermentation plays a crucial role in driving the eco-friendly transformation of the agricultural industry. Within this domain, the fermented beverage sector stands out due to its consumer-friendly appeal. To promote innovation in this field, there is a need for cost-effective, versatile and sustainable techniques that can accelerate research and development activities. In the bioprocess sector, innovation management requires consideration of an array of variables, including diverse raw materials, various microorganisms and different fermentation parameters. Direct injection mass spectrometry (DIMS) technologies offer solutions for bioprocess monitoring, particularly in the analysis of volatile organic compounds (VOCs) and are constantly improving their performance in terms of sensitivity and specificity. Among the DIMS methods, proton transfer reaction-mass spectrometry (PTR-MS), when coupled with autosampling and customised data handling and analysis, has demonstrated its efficiency in studying VOCs associated with fermentation. This approach brings automation to data production and management, offers exceptional versatility akin to a sensor and aligns closely with the principles of green chemistry. In this perspective paper, after reviewing key aspects of modern fermentation practice, we showcase the application of PTR-MS as a model to demonstrate its potential as sensor-like approach to drive innovation within the fermented beverage sector. This approach enables swift, large-scale assessments of multiple variables while providing comprehensive insights into the quality and safety of the final products.

Keywords Bioprocess, fermentation, quality, safety, sensors, volatile organic compounds.

Fermented beverages sector and the innovation trends

Consumer demand for healthy and sustainable products that taste great is steadily increasing because of the growing awareness of the importance of making food choices that promote the health of the planet as well as those of the individual (Valero-Cases *et al.*, 2020). Fermentation is a family of food bioprocess solutions that are well-known for transforming the sustainability, shelf life and sensory properties of raw materials into finished products, some of which, depend on fermentation type, might possess increased health-promoting attributes of the final products (Gao *et al.*, 2022; Xue *et al.*, 2024). Furthermore, fermentation processes support the circular economy by repurposing by-products and transforming waste into valuable resources, underscoring that they are highly cost-efficient methods for converting edible matrices with minimal energy and chemical inputs (Martin-Gómez *et al.*, 2024). This explains the trends observed in the global marketplace which focus on satisfying consumer expectations using fermentation as a driver of sustainable innovation (Valero-Cases *et al.*, 2020). Humankind, despite having knowledge of

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microorganisms for a only few centuries, has been carrying out food fermentations for millennia. This helps to explain the vast range of different fermented drinks that represent a heritage of humanity and a starting point for innovative paths in this field (Gänzle, 2022). The category includes fermented alcoholic beverages, which represent a progressively diverse and significant sector. Although they do not align with the health requirements of consumers, owing to their ethanol content, these beverages continue to hold substantial economic importance and remain intricately connected to traditional local production, particularly in the context of protected geographical indications (Capozzi *et al.*, 2020). In addition, emerging trends for non-alcoholic and low-alcoholic beverages create many challenges and opportunities, in addition to reducing the health cost associated with alcohol consumption (De Fusco *et al.*, 2019; Paredes *et al.*, 2022). However, challenges exist in achieving the flavour complexity and shelf life observed with alcoholic beverages. Overcoming these challenges will generate valuable opportunities for companies to develop innovative business strategies and new product development, exploiting novel fermentation cultures that produce alcoholic-like beverages with no or low alcohol (Tamang *et al.*, 2016). Overall, the non-alcoholic fermented beverages sector represents a rising and dynamic field in the food industry (Tireki, 2021).

Worldwide a broad array of several traditional beverages (e.g., yoghurt, beer, wine, kefir, *koumiss*, *airag*, *laban rayeb*, *leben*, *nunu*, *tarag* and *sua chua*) (Tamang *et al.*, 2016) are produced from different edible raw materials (e.g., milk, cereals, fruit juice, herbs and vegetables) (Fig. 1). Among these, traditional dairy drinks are the most commonly consumed in Western countries, with milk representing a good substrate for microbial growth and source of functional compounds/probiotic delivery (Gao *et al.*, 2021). The innovation of these products is currently built around enhancing the nutritional content (e.g., incorporating alternative sustainably produced proteins, mineral salts and/or vitamins) and improving the sensory properties (Tian *et al.*, 2023). Increasingly consumers are opting for a plant-based diets owing to sustainability, and ethical considerations, in addition to health considerations including milk allergies and intolerances. Raw materials of plant origin are potential substrates for the design of new fermented beverages as well as for traditional products. In general, these materials are a rich source of nutrients, for example, fermentable carbohydrates, organic acids and minerals that could promote the viability and metabolic activity of the desired microbes (Tang *et al.*, 2022). However, meeting consumers' needs requires solving major technological issues (e.g., non-optimal homogeneity, creaminess, density and flavour), and finding the appropriate fermentation conditions, including starter culture, raw materials, additional nutrients, fermentation temperature and oxygen requirements, to achieve reliable fermentative processes and desired characteristics (Hilgendorf *et al.*, 2024).

Fermented beverages, R&D needs and VOCs as versatile targets

Microbial metabolism represents a key phase in the desired transformations that occur in fermented products. It plays a critical role in enhancing product quality by generating compounds with aroma properties, antioxidant activity, or other functional features. This, in turn, can create opportunities for market diversification that makes various products capable of meeting consumer needs, including vegans and people wanting to make sustainable choices (Valero-Cases *et al.*, 2023). Not all foods are oriented at a broad consumer segment, with an emerging market category targeting dietary supplements and food best suited to individual well-being needs. Given the challenge of creating tailored products for personalised nutrition and health-promoting targets, one emerging trend in the food industry is the shift towards the manufacture of beverages for specific population segments (Ibrahim *et al.*, 2023). Improving traditional fermented beverages and developing new fermented products requires managing many variables (Fig. 1 and Fig. 2) and monitoring bioprocesses where understanding temporal dimension can be critical. As mentioned, there is a considerable variety of raw material options, ranging from animal products to various plant crops, including different breeds and cultivars. These raw materials may be combined with diverse microbial cultures, from eukaryotic to prokaryotic organisms including complex wild microbial inoculations, which can be explored for technological tasks (Tamang *et al.*, 2016). Generally, raw materials may include a variety of native microbes. Starter cultures are microbial biomass selected in quantity (number of cells) and quality (specific species/strains) to direct the fermentative process towards desirable attributes and compounds that can shape products sensory, nutritional and functional value (Gänzle *et al.*, 2023). These bioprocesses must be understood and monitored to ensure they proceed as expected to generate the expected final product quality (including sensory properties) and to limit possible undesired effects, such as excessive acidification and off-flavour production. Protechnological microbes, such as, yeasts (e.g., *Saccharomyces*, *Torulaspora, Metschnikowia, Candida and Hanseniaspora*) and bacteria (e.g., *Lactiplantibacillus, Lactococcus, Leuconostoc, Oenococcus, Pediococcus, Streptococcus* and *Weissella*) represent heterogeneous microbial categories, which contain large microbial biodiversity, in terms of

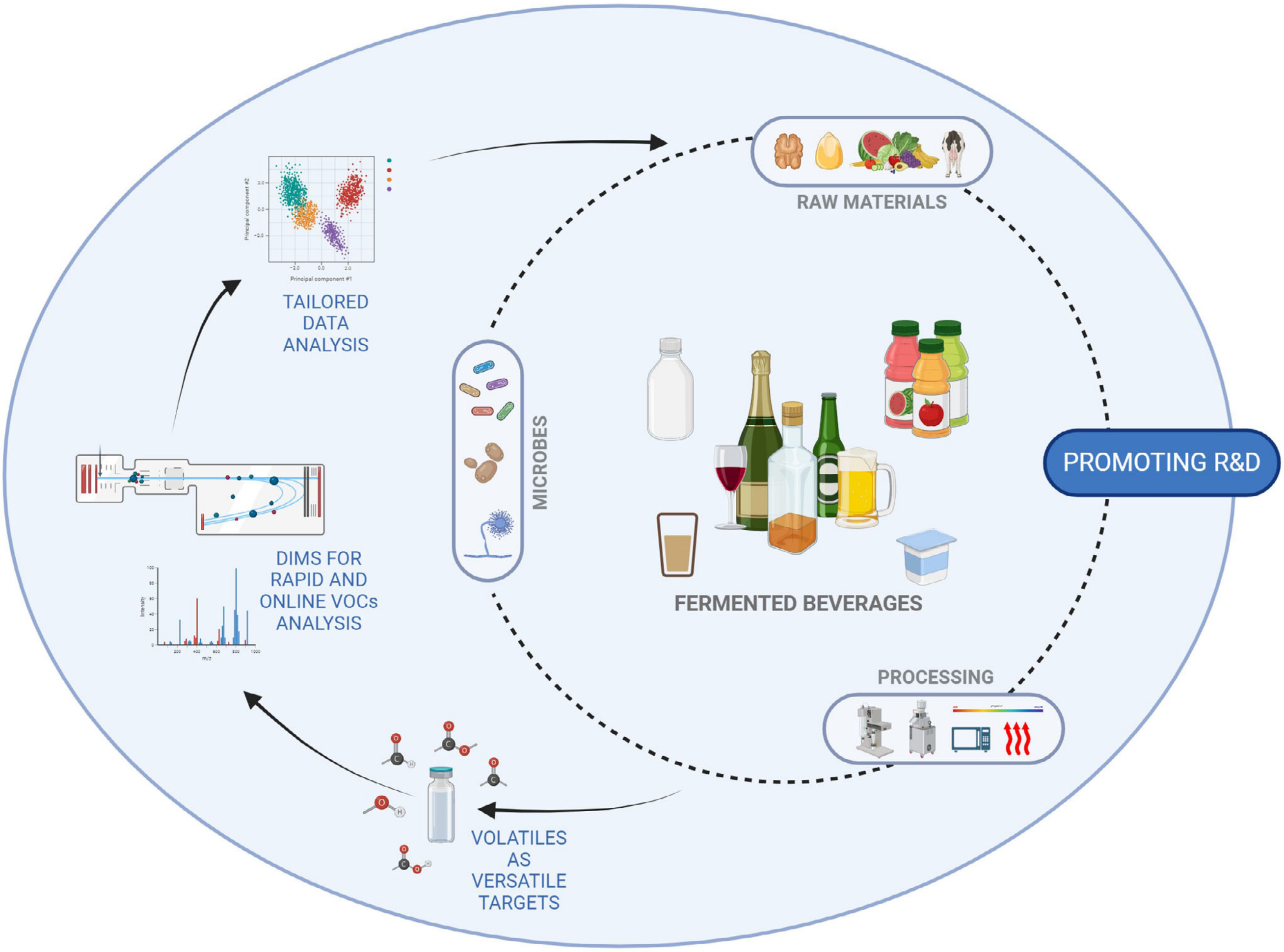

Figure 1 Variables involved in a fermented food process and analysis. The quality of fermented beverages is assessed by investigating volatile compounds using PTR-MS, which is an innovative analytical solution. This assessment takes into account process variables, the composition of raw materials and microbial biodiversity.

species/strains (Tamang *et al.*, 2016). At this point, it is important to highlight that the variables mentioned do not operate in isolation but rather interact thereby increasing the complexity and totality of variables needed to be considered in a defined environment/food. It is crucial to understand which microbial symbioses, technological parameters (e.g., temperature, pH and nutrients), different ingredients and food formulations are required to achieve a successful fermentation process (Capozzi *et al.*, 2021a). These variables impact the growth and metabolism of the microbial resources, which in turn affects the quality attributes (e.g., safety, nutrition, flavour, texture, colour and appearance) of the product are poorly understood, particularly in relation to consumer preferences, and presents a current challenge. Together with the application of starter cultures technology, there is also a growing interest in microbiomes as bioresources valorisable for fermentation, which is also a hot topic with respect to applications in beverage production (Olmo *et al.*, 2022). One of the challenges is the management of microbial communities exploited in backslopping practices, which involves the addition of a portion of the batch from the previous fermentations to fresh raw materials. This process can be repeated for several cycles until a stable fermenting microbiome is achieved, enhancing the overall quality and assuring the safety of end products. In addition, emerging applications of microbiomes are taking innovative approaches to understand fermentation mechanisms and biochemical pathways and then exploiting these aspects to generate innovation. Taking into account all these trends, therefore, one of the major bottlenecks limiting innovation in the fermented drinks sector is the availability of suitable on-line,

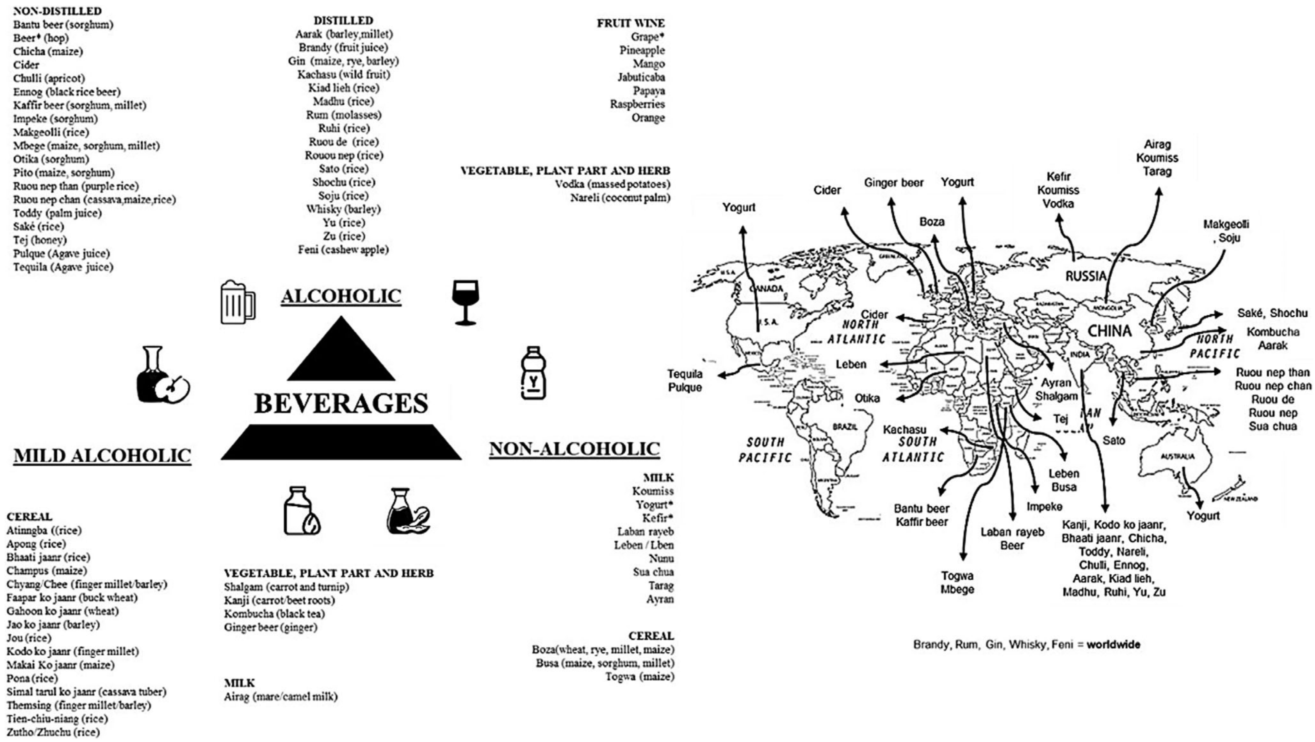

Figure 2 Traditional and new alcoholic and non-alcoholic beverage (Tamang *et al.*, 2016, 2020). Common and uncommon fermented beverages consumed worldwide and categorised in three groups: alcoholic, mild alcoholic and non-alcoholic beverages. * = beverages analysed also by PTR-ToF-MS.

informative and direct monitoring of fermentation, which is capable of large-scale screening to evaluate diverse raw materials/microbial resources. Monitoring and assessing new formulation/fermentative processes and evaluating the different sensory characteristics in traditional products can support product development, influencing beverage acceptability and changing consumer preferences and consumptions. This activity holds the utmost significance for industrial research and development. The changes occurring in beverages can be monitored by performing a quali-quantitative analysis of VOCs, which are general indicators of product quality and can provide targets to assist new product development. A large number of VOCs generated during fermentation are microbial secondary metabolites and can be used to determine the presence, absence and/or growth of bacteria, yeasts or filamentous fungi (Weisskopf *et al.*, 2021). For example, the evolution of flavour can be used to investigate the performance of autochthonous and commercial strains as single or mixed inocula, but also of microbiomes, in order to obtain integrated information on the *(i)* microbial growth, *(ii)* impact of fermentation on raw materials, *(iii)* phenomena strain dominance in complex mixtures and *(iv)* quality of the raw material/the finished product. Furthermore, this approach can be used to develop new products and design novel foods (Smolinska *et al.*, 2014). The complex interaction between microbes and edible matrices requires a careful investigation to understand the underlying bioprocesses, which can be achieved by monitoring VOCs. Conceptually, the idea is to define an analytical target or targets that are sufficiently versatile to accelerate the understanding of different fermentation processes through the use of sensor-like technology that can make data capture, analysis, interpretation and comprehension easier and faster (Smolinska *et al.*, 2014).

Traditional/innovative techniques for VOCs analysis and the potential of PTR-MS

The ideal method for determining VOCs should have high selectivity, sensitivity, resolution and a linear response across the required concentration ranges and, where possible, to be compliant with–the Green Analytical Chemistry guidelines (Sajid & Płotka-Wasylka, 2022). The conventional analytical approach for the identification and quantification of VOCs are gas chromatography (GC) techniques, but they are, in general, not suited for rapid, on-line analysis (Mazzucotelli *et al*., 2022). Resolution and detection limits for qualitative analysis of complex gaseous mixtures can be further improved using for example, multi-dimensional gas chromatography (MDGC). For quantitative analysis, these approaches require the use of standards, thereby increasing the cost of analysis and pollution. Additionally, sample preparation techniques risk misrepresenting the sample headspace and making the complex detection of gas mixtures more complicated, for example, solid-phase microextraction (SPME) or dynamic headspace (DHS) (Majchrzak *et al*., 2018). For these reasons, direct MS-based techniques are being investigated to obtain high throughput analysis across broad concentration ranges without the need for standards to quantify concentrations. Analysis times can be reduced by employing Fast GC, which consists of shorter chromatographic columns with faster oven temperature gradients and elevated linear carrier gas speeds. Limited sample capacity can result in low sensitivity; however, this can be improved using multicapillary columns (MCC). The use of manual injections reduces sample reproducibility but this can be offset through the use of quick valve switchover injections. Fast GC × GC, used for the first time in 2006 for the natural pyrethrins separation, is a leading example that captures the advantages mentioned above (Stefanuto *et al*., 2015). DIMS are among the alternative analytical methods applied to VOCs analysis (Mazzucotelli *et al*., 2022). These methods are receiving great interest as the measured signal (i.e., the mass/charge (m/z) ratio), provides useful information about the VOCs and some of their intrinsic properties (Majchrzak *et al*., 2018). Food science can take advantage of the ever-improving mass and time resolution of these ‘green’ methods (e.g., minimal sample size, no analytical waste, no sample treatment, automated methods, no toxic reagent and safety of operator). During the fermentation process, the release of secondary metabolites can rapidly change different product characteristics and require analytical techniques with high temporal resolution and high sensitivity to follow the evolution of these processes. PTR-MS, a DIMS technology, has a proven ability for on-line measurement of VOCs and able to carry out multiple measurements within a very short timeframe combined with high-sensitivity and non-destructive sampling (Nenadis *et al*., 2016). PTR-MS is termed a ‘soft ionisation’ technique because of the low reaction energy used during ionisation, which causes very little fragmentation of the parent ions. Therefore, interpreting the spectrum and quantifying the compounds is much easier compared to electronic impact ionisation. The early PTR-MS models possessed a quadrupole mass detector that is preferentially used for the targeted analysis of compounds, especially known compounds such as drugs and pollutants, since the mass resolution is limited to the nominal mass (Yuan *et al*., 2017). When no information is known about the VOCs present in a sample, ion trap and time-of-flight (ToF) mass analysers (Lubes & Goodarzi, 2017) are the preferred detectors to be coupled with PTR-MS due to the increased chemical information obtained, which allows simultaneous investigations of many compounds within a complex gas mixture, allowing tentative identifications based on very accurate information of the mass of the ion. In particular, TOF analysers are widely applied across many fields because they offer better temporal resolution and mass range than quadrupoles (Yuan *et al*., 2016). Ion mass is based upon ion flight time measured upon reaching the detector, where lighter ions travel faster than heavier ones. Typically, a full spectrum is obtained within 1 s, although higher time resolution can be attained depending upon the signal to noise ratio. The latest PTR-MS devices offer detection limits lower than 0.1 pptv (e.g., PTR-TOF 10 K from Ionicon), however, in practice, the measurement range typically spans from a few ppbv to a few ppm (Majchrzak *et al*., 2021). Even if the operating conditions are optimised to reduce the formation of water clusters and fragmentation of product ions, the high heterogeneity and chemical diversity of food matrices under the selected experimental conditions mean that ionisation can lead to fragmentation dynamics that make identification of VOCs difficult, for example, the presence of ethanol in the matrix (Romano *et al*., 2023). In this situation, a first solution is to dilute the VOCs directly on the sample or during headspace injection (e.g., employing argon as buffer gas), to reduce the negative effect of the interferent. Another opportunity is to ‘reduce the drift field’ in order to modulate the energy delivered in ion-molecule collisions (Romano *et al*., 2023). Also, switching to other reagent ions, such as NO^+, O_2^+, Kr^+ and Xe^+, can help by extending the number of VOCs detected and increase the chemical information obtained (Cappellin *et al*., 2013).

To help overcome VOC identification challenges, PTR-MS can be partially paired with limited GC–MS analysis. Some key experimental variables can also be analysed with the GC, leaving the PTR to study all samples. The combined utilisation of these two techniques allows to obtain the respective advantages: *(i)* gathering chemical data of sample or containing uncharacterised VOCs (GC-MS), and *(ii)* conducting sophisticated and extensive experimental designs with large scale, high temporal resolution and real-time monitoring (PTR-MS). The combined use of gas chromatographic separation with PTR-MS analysis is also possible, where the sample VOCs are separated by chromatographic column (Fast GC analysis) before entering the PTR-MS device. This allows obtaining the retention time as an additional VOCs identification tool and increases data quality by allowing separation of isobaric compounds, also offering an additional solution to reduce the impact of interferents (Romano *et al.*, 2023). Nevertheless, this approach is not perfectly suitable for accurate, high temporal resolution, real-time analysis (Isaacman-VanWertz *et al.*, 2018), due to the additional analysis time (about 180 s per sample) and uncertainty over injection time.

Emerging evidence on the potential of PTR-MS as rapid, direct and high-sensitivity sensors in fermented beverages

The literature describes the application of the DIMS, and, in particular, PTR-MS, to characterise the diversity of VOCs produced during fermentation studies, including some evidence about microbial-based bioprocesses. Table 1 summarises how PTR-MS approaches have been exploited to address specific challenges in the field of food fermentations. This analytical strategy has proven interesting insights in the discrimination of *(i)* different microbial resources, *(ii)* interaction between raw matrices (ingredients) and microbes and *(iii)* microbial interactions (Table 1), representing the main categories into which the innovation paths in the design of fermented products fall. For instance, the research study by Benozzi *et al.* (2015) serves as a prime example of how PTR-MS is suitable for designing food fermentation processes. This technique efficiently selected and characterised new microbial starter cultures based on their aromatic potential. Four distinct yoghurt starter cultures were monitored during lactic acid fermentation with minimal manual intervention. Based upon the PTR-MS measurements of VOCs collected on-line, Yépez *et al.* (2019) selected the best combination of LAB starter and cereal matrix for fermented dairy analogue development, comparing the trials with standard milk-based products. Berbegal *et al.* (2020) employed PTR-ToF-MS to conduct a detailed experiment involving 14 different combinations of *Saccharomyces* and non-*Saccharomyces* strains inoculated in grape juice and must. In addition to fermentation application, PTR-MS monitoring has proven effective in studying microbial spoilage phenomena, demonstrating the potential in analysis where microorganisms are protagonists. For instance, Alothman *et al.* (2023) applied, for the first time, PTR-MS together with microbial analysis and consumer testing to understand what leads the consumer to reject pasteurised milk. Investigations using PTR-MS have successfully explored not only the use of pure biomass from eukaryotic and prokaryotic resources but also bioprocesses involving complex consortia (Table 1). In term of matrix diversity (Tamang *et al.*, 2016), these studies have explored VOCs generation in dairy (e.g., milk kefir, yoghurt), bakery, meat, cereal-based beverage, alcoholic beverages (e.g., beer, wine) and miscellaneous fermented products (e.g., cocoa bean) (Table 1). The case studies reported the potential of PTR-ToF-MS for the generation/release of multiple VOCs during the fermentation process and in the resulting products. Furthermore, these studies aim to comprehend the impact of various experimental variables on the release of these VOCs and the time of generation throughout the microbial growth process. These studies demonstrate VOCs measurements using PTR-TOF-MS technology's ability to monitor the impact of multiple variables involved in bioprocesses in a manner that is consistent with Green Analytical Chemistry guidelines and allows insight into metabolic and product quality changes during fermentation (Mazzucotelli *et al.*, 2022).

This perspective highlights the importance of utilising DIMS in a sensor-like approach, albeit with much richer chemical information. Applications in the areas discussed have the potential to greatly impact the fermented beverage sector by setting VOCs as analytical targets to achieve specific sensory characteristics, thereby promoting innovation, particularly for plant-based dairy analogues. As well, this approach can expedite the process of carrying out large-scale screening of variables, time-dependent evaluations and to offer more comprehensive insights into various product quality and production safety aspects (Smolinska *et al.*, 2014; Mazzucotelli *et al.*, 2022). It is increasingly clear that fermentation and microbial biotechnology wield tremendous potential in facilitating a green transition within food systems, especially in the versatile beverage sector (Materia *et al.*, 2021; Rastogi *et al.*, 2022). In general, with the exception of partial applications in yoghurt and alcoholic beverages, PTR-based solutions have been poorly explored in the processed beverage sector through the development of prokaryotic and eukaryotic microbes. In particular, a paucity of data on VOCs generation and changes in fermented dairy analogues presents a significant bottleneck in maximising the aforementioned potential, considering the recent trends characterising the sustainable evolution of food systems, in order to promote tailored nutrition while minimising the environmental impact on environmental resources.

The outlined analytical approaches offer economic benefits with high throughput and automated analysis, providing a low cost per test. This is important as the food industry primarily consists of small and medium-sized enterprises with affordable paths for conducting efficient research and development (Rastogi *et al.*, 2022). The financial stress is exacerbated by beverages largely falling into the low-value-added industries category (similar to a significant portion of the food industry, except for a few select markets), meaning that expenses associated with overseeing Research and Development (R&D) can provide a major hurdle towards fostering innovation (Rastogi *et al.*, 2022).

Table 1 List of scientific studies using PTR-ToF-MS to monitor volatile organic compounds during or at the end of a bioprocess in the food fermented sector

Experimental challenge	Matrix	Microbial resources	Research microbial phenomena	Mode	PTR-MS application	Reference
Different microbial resources	Yoghurt	*Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *Bulgaricus starter culture*	Lactic acid fermentation	Online monitoring	Selecting the appropriate microbial resources for their aroma profile to monitor and design the yoghurt production process	Benozzi *et al.*, 2015
Different microbial resources	Yeast extract peptone dextrose YPD Growth Agar	*Saccharomyces cerevisiae* strains	Alcoholic fermentation	Online monitoring	Differentiating volatilomes of genetically similar strains of oenological relevance during the whole growing process	Khomenko *et al.*, 2017
Different microbial resources	Bread	*Saccharomyces cerevisiae*	Alcoholic fermentation	Online monitoring and screening	Studying VOCs evolution during the leavening process and upon baking of dough samples	Makhoul *et al.*, 2014
Different microbial resources	Wine	*Oenococcus oeni* strains	Alcoholic and malolactic fermentation	Screening	Identifying wines from different geographical origins and wines fermented with different malolactic starters from VOCs profile.	Campbell-Sills *et al.*, 2016
Different microbial resources	Bread dough	*Saccharomyces cerevisiae* strains	Alcoholic fermentation	Online monitoring	Finding VOCs markers to characterise starter cultures isolated from alcoholic beverages and to use as flavouring agents for bakery products.	Capozzi *et al.*, 2016
Different microbial resources	Cocoa beans	Microbial consortia	Spontaneous cocoa fermentation	Screening	Discriminating fermented and dried cocoa beans of various provenance based on volatile and spectral profiles	Acierno *et al.*, 2019
Different microbial resources-Interaction raw matrix/microbe	Milk kefir and cereal kefir-like products	*Lactobacillus plantarum* and *Leuconostoc mesenteroides* strains	Lactic acid fermentation	Online monitoring	Evaluating LAB strains based on flavour release to improve vitamin B2 content in kefir-like cereal-based beverages	Yépez *et al.*, 2019

Table 1 (*Continued*)

Experimental challenge	Matrix	Microbial resources	Research microbial phenomena	Mode	PTR-MS application	Reference
Interaction raw matrix/microbes	Yoghurt	Commercial starter culture	Lactic acid fermentation	Online monitoring	Illustrating the impact of matrix composition and structure on the release of flavour compounds formed during lactic acid fermentation in real products.	Soukoulis *et al.*, 2012
Interaction raw matrix/microbe	Bread	*Saccharomyces cerevisiae* strains	Alcoholic fermentation	Online monitoring	Examining the changes in VOCs during leavening and baking	Makhoul *et al.*, 2015
Interaction raw matrix/microbe	Gluten-free bread	*Saccharomyces cerevisiae*	Alcoholic fermentation	Screening	Exploring alternative methods to the gold standard bread aroma analysis GC–MS for evaluating the impact of baking time on both baked and toasted bread crumb and crust samples	Pico *et al.*, 2018
Interaction raw matrix/microbe	Beer	*Saccharomyces cerevisiae*	Alcoholic fermentation	Online monitoring	Monitoring VOCs development to investigate the hop-yeast impact on aroma perception	Richter *et al.*, 2018
Interaction raw matrix/microbe	Gluten-free bread dough	*Saccharomyces cerevisiae*	Alcoholic fermentation	Online monitoring	Understanding of the production and release of volatile compounds during the baking process of five distinct gluten-free bread varieties to elucidate the residual volatiles present in the final crumb and crust, which contribute to the perceived flavour experienced by consumers	Pico *et al.*, 2020
Interaction raw matrix/microbe	Beer	*Saccharomyces cerevisiae*	Alcoholic fermentation	Screening	Investigating the differences in VOCs and sensory properties to determine the impact of hop origin on beer aroma	Taiti *et al.*, 2020
Microbial interactions	Wine	*Saccharomyces cerevisiae* strains and non-*Saccharomyces* strains	Alcoholic fermentation	Online monitoring	Evaluating the best single or mixed starter cultures to promote alcoholic fermentation and typical volatile compounds of wine.	Berbegal *et al.*, 2020

Table 1 (*Continued*)

Experimental challenge	Matrix	Microbial resources	Research microbial phenomena	Mode	PTR-MS application	Reference
Microbial spoilage monitoring	Milk	Native spoilage microbes	Microbial spoilage	Screening	Understanding the progression of food spoilage and consumer's decisions to reject a product starting from VOCs composition combined with the Rejection Threshold and microbial analyses	Alothman *et al.*, 2023
Microbial spoilage monitoring	Beef meat	Native spoilage microbes	Microbial spoilage	Online monitoring	Identifying VOC markers in packaged meat to assess optimal shelf life	Franke *et al.*, 2019
Microbial spoilage monitoring	Chicken poultry	Native spoilage microbes	Microbial spoilage	Online monitoring	VOCs, storage time, and microbial analysis were used to classify the freshness of poultry samples.s	Wojnowski *et al.*, 2018

Fermented beverages, however, stand as a subcategory where it is possible to extract larger margins, which, if successful, could create increased returns for small and medium-sized enterprises. An opportunity exists here for sensor-based approaches of the kind discussed in this perspective to utilise public–private research collaborations to cost-effectively exploit untapped innovative solutions. The proposed overview in terms of challenges/case studies demonstrates the potential in terms of application versatility. It should also be mentioned that one of the food system goals is to attain the utmost productivity and profits, as long as their methods adhere to environmental boundaries to lessen the impact of climate change and guarantee global ecological sustainability. In this context, food fermentation technology is particularly advantageous due to its accessibility, cost-effectiveness and positive impact on the environment, making it a preferred choice over alternative methods. That is the reason why it is highly relevant in many research fields related to manufacture, improvement and subsequent phases of pharmaceuticals and biologics, bio-fuels, bio-fertilisers, biodegradable polymers, etc. (Rastogi *et al.*, 2022). Moreover, DIMS, used in a sensor-like approach, offers exciting analytical solutions due to the high degree of automation from data generation (VOC analysis) to data production and management and for compliance with several of the principles of green chemistry (Capozzi *et al.*, 2017; Mazzucotelli *et al.*, 2022). From the perspectives outlined, it is crucial to recognise that DIMS analytical strategies allow rapid, frequent, non-destructive and effective analysis of VOCs, which enables extensive monitoring of VOCs, including secondary metabolites, across both primary products and processed commodities. The resulting information can be used in many ways, from the design of improved starter cultures to improved fermentation processes, enhanced understanding of flavour generation during fermentation and control of sensory attributes through fermentation (Capozzi *et al.*, 2021b). Ultimately, the outcomes from DIMS analytical strategies provide benefits to all stakeholders, including consumers, enterprises, government agencies and academia (Mazzucotelli *et al.*, 2022). The expansion of research towards the use of sensor-based approaches to characterise food systems, including food matrices, shows the potential to grow the number and complexity of transdisciplinary studies in biological and technological processes.

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Author contributions

Antonia Corvino: Writing – original draft; conceptualization. **Pat Silcock:** Conceptualization; writing – review and editing. **Vittorio Capozzi:** Conceptualization; writing – original draft. **Franco Biasioli:** Conceptualization; writing – review and editing; funding acquisition; resources.

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Data availability statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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