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Food systems microbiome-related educational needs

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Abstract

Within the European-funded Coordination and Support Action MicrobiomeSupport (https://www.microbiomesupport.eu/), the Workshop 'Education in Food Systems Microbiome Related Sciences: Needs for Universities, Industry and Public Health Systems' brought together over 70 researchers, public health and industry partners from all over the world to work on elaborating microbiome-related educational needs in food systems. This publication provides a summary of discussions held during and after the workshop and the resulting recommendations.

BACKGROUND

In the last two decades, microbiome science has been a constantly growing interdisciplinary research field connected to diverse areas (such as agriculture, biotechnology, environmental research, food science, one health, plant research, regulatory science and [veterinary] medicines). The term 'microbiome' refers to a microbial community (including prokaryotes, fungi, protozoa and other micro-eukaryotes) inhabiting a particular habitat and also encompasses their 'theatre of activity' (microbial structures, metabolites/signal molecules and mobile genetic elements, including transposons, phages, viruses and relic DNA), resulting in the formation of specific ecological niches (Berg et al., 2020). Microbial communities exist in different environments across the whole food ecosystem: in and on food, fodder and forage crop roots in soil, on plants and algae, on fruits and vegetables, in foods that have been fermented or brewed, on and in animals and humans, in aqueous environments where food is grown or harvested, as well as in food-producing and processing facilities, which often harbour an autochthonous microbiota (Cavicchioli et al., 2019; Małyska et al., 2019). Food systems act at the intersection of many crucial challenges we face today: from fighting climate change to halting biodiversity loss and reducing waste, where they play a key role. Circular economy approaches, which consider interdisciplinary networks, will be necessary to sustainably feed our growing human population.

The citizen's perception of microorganisms is generally negative, due to their association with disease and food spoilage (Simard, 2021). However, the vast majority of the planet's microorganisms are not pathogenic (Balloux & van Dorp, 2017), and in many cases, we rely on their ability to break down a wide range of substrates to maintain the cycling of elements, disposal of sewage, remediation of toxic materials, composting, producing fermented food and more (Hou et al., 2020; Insam & de Bertoldi, 2007; Nascimento et al., 2018; Olmo et al., 2022; Parvez et al., 2006). Timmis et al. (2019) consider that there is an urgent need for microbiology literacy in our society, because microbial activities affect everyone in diverse ways and are key for sustainable and economic development (Callens et al., 2022; D'Hondt et al., 2021). To take appropriate, evidence-based decisions in many spheres at all levels, an understanding of relevant aspects of microbiology, including microbiomes, are essential. Thus, microbiology literacy is essential for the transition to knowledge-based stewardship of our lives, the biosphere and the planet. To contribute to the microbiology literacy of our society, we need to explore every available resource to communicate the discipline in a clear and appealing way. This will involve a transformation in educational communication and optimization in teaching that produces a balanced and comprehensive understanding of microbiomes so that young people can interpret and better understand many phenomena in their daily lives, and in general, on Earth. Communication between researchers, innovators, policymakers, regulatory bodies, industry actors, technology users (including farmers) and civil society is also needed to ensure that microbiome innovations can be applied and commercialized in the near future.

In this frame, the workshop was organized to discuss and gather expert opinions directly from a broad-spectrum of stakeholders representing the scientific community, public health bodies and industry business champions where food systems microbiome research plays a crucial role. In this workshop, the necessity of defining the educational needs of microbiome-based research for public health bodies and precision food/medicine-based concepts and creating awareness about the academic implementation of microbiome-related learning goals and life-long learning concepts were also elaborated.

The role of science communication is significant in terms of raising awareness. However, there might be different drivers behind the development, delivery and evaluation of the science events: (1) disseminating research outputs as required by funding bodies; (2) using the public as citizen scientists to contribute to data generation or analyses, as funders of the work through crowdsourcing or as obligatory part in third-party funded research projects; (3) reinforcing a key message (such as the importance of gut health or health of the immune system related to the microbiome); and/or (4) enhancing science and microbiology literacy (Timmis et al., 2019). Social networks are becoming more and more important to teach and engage people about the importance of science. The integration of communication services in the universities and research centre's structures, which take over responsibilities for social media networking, is strongly recommended to enhance their visibility, share and communicate science to society, promote scientific culture and use it as a tool for teaching and learning.

Here, we present a summary of the workshop discussions in the context of the key themes such as educational needs in food systems microbiome research for public health, academia and industry.

PUBLIC HEALTH

Until now, a considerable degree of public 'education' on the microbiome takes place in the press, science communication books or journals, and on social media, with the main focus being the human gut microbiome (Shan et al., 2019). Numerous studies have been carried out indicating that human consumption of beneficial microbiota-rich foods from infancy onwards can improve public health now and in the future (Matsuyama et al., 2019; Singh et al., 2017). Most of the public knowledge on microbiomes is limited to the health benefits of microbiota in humans through dietary changes (Marco et al., 2017). Nevertheless, the microbiome field in the context of human health for products and therapeutics is obviously relevant. It presents somewhat different but partially overlapping opportunities, such as health and microbial transplants (Gupta et al., 2016), probiotics and dietary supplements (Kerry et al., 2018), starter cultures and fermented foods for health and nutrition (Marco et al., 2017), infectious disease and the rise of antibiotic resistance (Laxminarayan et al., 2020; Majumder et al., 2020) and more. As microbiomes have multiple important functions for the human body (Gilbert et al., 2018), there is a need to improve citizens' knowledge about the importance of microbiomes. It is crucial to raise awareness of the potential of microbiomes among the citizens to understand potential benefits and concerns, as well as share opportunities for using microbes for a future-proof food system. If the citizens understand the benefits of microbiome products or therapeutic suggestions, the acceptability of microbiome applications in society should increase.

The workshop discussion revealed that translating knowledge from bench to bedside is of crucial importance. Thereby, ensuring that microbiome awareness and information will reach healthcare professionals and the broader audience (Table 1). One possibility could be increasing education campaigns to raise public awareness. Ultimately, good science, sound marketing and consumer education are key when it comes to broadening the scope of food systems' microbiome innovations. New concepts need time to settle, but consumers are open to trying novel and innovative suggestions if they can understand the advantages and benefits. Benefits should be communicated clearly, but without making irresponsible claims. Motivated consumers seek trusted, science-based guidance and tailored solutions. Another important demand is that consumer rights must be respected by ensuring transparency through the implementation of clear labeling rules for microbiome products. Microbiome research has recently gained centre stage in both basic science and translational applications. However, scientists often feel that public communication about the potential of microbiome research is overpromised. A good way for scientists would be to engage in more open, ethical and transparent communication about food systems' microbiomes. Open and transparent communication from early on in innovation pathways mainly increases trust in scientific processes and thus paves the way to achieving societal milestones such as the United Nations Sustainable Development Goals (SDGs; United Nations, 2015) and The European Green Deal (2019). Given the current excitement about the microbiome in the media, serious investment in school and adult education is called for, to ensure a microbiome-literate society.

The impact of the microbiome on human, animal and/or environmental health is considered but not yet ready to be applied in food and feed safety assessments by the European Food Safety Authority (EFSA) or by other national or international regulatory agencies (Merten et al., 2020). There is a need to perform a prospective mapping of the roles of microbiomes with a view to understanding their potential impact on a system's equilibrium. Awareness of microbiome–health interactions by healthcare professionals as well as patients and consumers are essential in advancing personalized disease prevention concepts of non-communicable disease (NCD). Individualized healthcare concepts are a great way to take responsible actions. It would be convenient to leverage the 'curiosity' that consumers have in optimizing

TABLE 1 Summarized list of main needs and immediate, mid- and long-term actions recommended at different levels of public health and who is responsible for taking what type of action to address these needs elaborated during the workshop.

	Needs	Recommended actions	Who (actors)
Public health	Create awareness of microbiome–health interactions	Education and awareness programmes to improve public knowledge, generate curiosity, consumer acceptance and boost the action of one's own health	Healthcare professionals Public Health Officials
		Increased awareness: • Disseminate clear and real messages in the microbiome communications • First take-up of 'microbiome' in commercials • MicrobiomeSupport and other public projects can bring messages to society	Healthcare professionals/companies Governmentally funded microbiome projects
	Raise awareness among governments, politicians and regulatory stakeholders on the need to support food systems microbiome research	Workshops and Symposia Trans-sectorial dialogue opportunities	Neutral dialogue platforms (EUFIC) International Life Sciences Institute (ILSI) Governmentally funded microbiome projects Risk assessors
	Need for microbiome literacy in the society	Create and support initiatives such as the International Microbiology Literacy Initiative (IMiLI)	Microbiologists Learned Societies
		Promote and integrate online learning platform courses, such as the MOOC course about microbiome and health performed by the Institute of Environmental Biotechnology (TU Graz, Austria) or the online open course 'The Human Microbiome' (EIT Food)	Public Health Institutions Research Institutes Universities Schools

lifestyle and to increase incentives for NCD prevention (Ruthsatz et al., 2020). Previous studies show that many healthcare professionals only have a medium understanding of what probiotics are and how they work, although they recognize that probiotics have a place in clinical medicine and would recommend them if they had more information to support informed decision-making within patient care (Fijan et al., 2019; Wilson & Whitehead, 2019). Therefore, there is a need for knowledge dissemination tools to summarize and translate the efficacy and safety information of probiotics, prebiotics and symbiotics to consumers, patients and healthcare professionals.

The Institute for Molecular Bioscience (The University of Queensland, Australia) has initiated a wide citizen science initiative called 'Soils for Science' to engage and inform the public on the origin and use of antibiotics, the challenge of antibiotic resistance, the urgent need for new antibiotics and the value of soil and soil microbes as a means to discover next-generation antimicrobials. The initiative is also offering kits to encourage people to donate them soil from different regions in Australia in order to develop downstream analyses towards the identification of novel potential antimicrobials (https://imb.uq.edu.au/soilsforscience).

Lastly, it is important to get the right message to the citizens, patients, regulators, risk assessors and healthcare providers to move from hype to reality, agree on opportunities, translate knowledge and disseminate it, implement policies and solutions quickly and provide dedicated training for healthcare professionals.

SCHOOLS AND NON-ACADEMIC TRAININGS

Microbiological education programmes targeting young people are expected to contribute to a future generation of scientifically literate users. Early education to improve knowledge about microorganisms and to promote using an adequate, scientifically correct language does allow children to express themselves better on the subject and encourage more rounded learning (Byrne et al., 2009).

Literacy needs to be created in school and the schools need curricula for the educational tasks. The International Microbiology Literacy Initiative (IMiLI; Timmis et al., 2019) was launched with the goal of creating microbiology literacy through the development of a school curriculum of societally relevant microbiology, and supporting resources, all of which will be made freely available. IMiLI is an international effort currently involving more than 500 well-known and early-stage microbiologists from many countries working pro bono to create a comprehensive collection of educational resources. The aim of this initiative is not to create microbiologists, but rather to engender new adult generations that know enough about relevant microbiological processes to be able to take informed evidence-based decisions at all levels, some of which also improve the well-being of humanity and the planet, and more effectively confront the challenges and global crises they will face. Since microbes play a crucial role in global crises such as extreme weather events caused by global warming, the COVID-19 pandemic, growing antibiotic resistance of microbial pathogens, starvation and lack of clean water in parts of the world and pervasive persistent pollutants and so forth, either as causes or potential solutions (Hernando-Amado et al., 2019; Timmis et al., 2022). To do this, the IMiLI seeks to generate curiosity and excitement about microbes and their activities in children and to inform them how microbes affect us in our everyday lives and how important such activities are for our well-being and that of the planet. In addition, to communicating societally relevant microbiology, the IMiLI teaching materials inform about sustainability, human stewardship of the biosphere and stakeholder responsibilities (Timmis, 2022). IMiLI also makes considerable efforts to provide specific visualization aids/mechanisms. These include, but are not restricted to multimedia teacher aids (such as images, cartoons, comics, videos, video games), class experiments (e.g. making yogurt, pizza or sourdough), hands-on activities that can get children in direct contact with the microbes and class excursions (McGenity et al., 2020), designed to immerse children in diverse examples of practical microbiology in their localities so that they (and, collaterally, their families and friends) mentally connect everyday experiences with the underlying microbes and their activities.

Social media, together with other media channels, can help to spread food systems microbiome news that can precipitate class debates on topical and/or controversial issues. Social media can also provide a vehicle for teaching microbiology in an open and accessible way, using a range of approaches from informative cartoons to interactive courses (López-Goñi et al., 2016; López-Goñi & Sánchez-Angulo, 2018). Comics, with their visuals and narrative, are also an innovative, agreeable and alternative way to learn about microbiology (Morel et al., 2019; Scavone et al., 2019). Moreover, new technologies developed by Oxford Nanopore have made it possible to bring DNA sequencing from the lab to the classroom. This is enabled by portable and affordable sequencers, which are barely larger than a smartphone and can collect microbial sequence data in real-time. Simplified, cloud-based data analyses can then provide tangible outputs for students, such as species identification based on phylogenetic trees, without requiring any specialized bioinformatics knowledge (Oxford Nanopore Technologies, 2022). Furthermore, the ease of library preparation with the various Oxford Nanopore library preparation kits allows students to do the lab work themselves and completes it within the limited timeframe of a school day (Salazar et al., 2020).

As the body of knowledge generated by microbiome research rapidly evolves (Berg et al., 2020), schools cannot keep pace with the dissemination of the latest research findings among students. In order to include recent findings in school curricula, it is necessary to incorporate microbiology teaching curricula in tertiary education and offer regular workshops for biology teachers on the topic. For example, Graz University of Technology (TU Graz, Austria) offered in 2021 a workshop for teachers on the recent findings in plant microbiome research. It is also important to make it easier for teachers to visit such workshops by education policymakers and to acknowledge it by implementing these workshops in continuing education programmes for teachers.

In the context of an ongoing worldwide pandemic, the culture of human hygiene has undergone a dramatic about-face, leaving the public in a state of bewilderment and generalized mistrust of science. A fundamental understanding of how we as humans can safely co-exist with microorganisms must be re-introduced, which requires the rewriting of school curricula. Students have been exposed to a barrage of media reports on the topic of the COVID-19 disease over 3 years which has raised many new and generally unanswered questions about microbes, and in particular viruses and diseases. While pathogens indeed constitute a major and growing health threat, it is essential to counterbalance public perception of microbes by educating society about the positive, undeniably crucial roles microbes play in the health of the biosphere, the economy and our daily lives (D'Hondt et al., 2021). It was concluded in the workshop that in the current climate of over-exposure to unfiltered media and misinformed adults, the challenge of disseminating the recent findings of microbiome research in an age-appropriate, pedagogically sound and creatively appealing, multi-sensory way should be supported by schools, higher institutions as well as political systems. Moreover, educating children and teachers about the importance of microbiome research has a carry-on effect, as students become disseminators of microbiome knowledge, as they share what they have learned with their family and friends (Timmis et al., 2020).

Teaching initiatives and outreach

During the workshop, some food systems microbiome teaching initiatives and online tools were presented. Most of the online tools are focused on the human microbiome, with comparatively few materials specifically related to disseminating knowledge on the topic of the environmental microbiome. For example, the 'Guardians of the Gut' website focuses on the gut microbiota, introduces key microbes and teaches about how antibiotics may upset the healthy microbial balance in the gut (https://guardiansofthegut.org/). The American Museum of Natural History has a well-thought-out science website for children, including online videos, games, stories and hands-on activities, aiming to cover the full sector of microbiology (https://www.amnh.org/explore/ology/microbiology). There are other examples of microbiome literacy-raising activities targeting children and adults, including the microbiome-awareness initiative 'The World Microbiome Day' (https://worldmicrobiomeday.com/), 'International Microorganism Day' (https://www.internationalmicroorganismday.org/) and the Museum of Microorganisms in Amsterdam 'Micropia' (https://www.micropia.nl/en/). Microbiome-related knowledge may be distributed to children at various public events such as 'European Researcher's Night' in some European Cities, 'Summer School KinderUni' in Austria or 'Science is Wonderful' exhibitions in Belgium. These initiatives, however, are not usually directly linked to the local schools and require a high degree of self-motivation for the participating scientific institutions, children and adults.

The Institute of Environmental Biotechnology (TU Graz, Austria) has been involved in microbiome–knowledge transfer activities for children for the past 10 years. They recently developed an online MOOC course about Microbiome and Health available for free to children and adults (https://imoox.at/course/microbiome). The 'Apple Microbiome' project also developed by TU Graz (https://apfelmikrobiom.tugraz.at/) taught children about the microbial composition of fruits and vegetables, increased their ability to make well-informed, healthy food choices and allowed them to work in a lab with the purpose of disseminating science. Another recent project 'Microbiome 4 Future!' (https://microbiome4future.tugraz.at/) allowed over 700 young people from 17 Austrian educational institutions to learn about microbiome directly from scientists. The programme included in addition to hands-on experiments, learning games and creative science transfer activities. These kinds of projects allow children and young adults to come in direct contact with scientists and scientific questions and participate in real-life research thus increasing their motivation for learning and understanding the subject. These projects have also made significant contributions to the visibility of research outputs, such as the fact that one of the publications resulting from the 'Apple Microbiome' project (Wassermann et al., 2019) became one of the top 100 publications scored by Altimetric in 2019.

Other examples are the initiatives carried out by Teagasc and APC Microbiome Ireland. A series of programmes and festivals were organized, from education to the arts, to increase the impact and reach of microbiome research and raise awareness of the microbiome importance to educators, the general public and policymakers. One of the events was 'Back to the

Future' for the Science Week 2020 programme, and the objective was among others to demonstrate how microbiome analysis on fermented foods is performed in the lab. Additionally, the 'STEM-Art projects' promoted the broader societal impact of the microbiome through collaboration with the arts (such as the 'Circadian Rhythms' exhibition at University College Cork or 'You are an Ecosystem' a book written by Laura Gowers). In Austria, a recently governmentally funded 3-year project named 'Micro-Tramper', organized by the University of Veterinary Medicine Vienna (https://www.sparklingscience.at/en/show-project.html?--typo3_neos_nodetypes-page[id]=1285; Austria), will focus on knowledge transfer in food microbiome research, targeting pupils and teachers in Federal Secondary Colleges. The project leverages Oxford Nanopore's MinION benchtop sequencer and software to evaluate and process samples from refrigerators, in-school produced cheese and local family farms. The students will learn how to analyse and interpret simple bioinformatic data with the goal of understanding the role of microbial diversity. The benchtop sequencers will also remain at the schools for microbiome sequencing projects to be regularly integrated into the school curriculum. The workshop participants are convinced that the implementation of similar dissemination initiatives can significantly improve the efficiency of microbiome knowledge transfer in schools with far-reaching, beneficial outcomes for human and environmental health, bolstering high-quality ongoing research in the field of food systems microbiome research and fostering a new generation of dedicated scientists.

The European-funded coordination and support action MicrobiomeSupport has developed a series of free resources (such as infographics, videos, factsheets, colouring book; https://www.microbiomesupport.eu/resources/) in order to disseminate the project and microbiomes in the food systems. MicrobiomeSupport has collaborated with other EU microbiome projects to form the #Microbiomes4Life cluster (https://www.microbiomesupport.eu/project-partners-2/) which aims at increasing awareness of the importance of microbiomes in the food system and improving public acceptance of potential microbiome innovations. All these initiatives contribute to greater dissemination of microbiome research in society, bringing science not only to the school students but also to the citizens.

UNIVERSITIES

Scientific career tracks are usually driven by the ability to conduct research and publish related results, and also to generate innovations as well as leverage the visibility of these research results and innovations. An understanding of the FAIR (Findable, Accessible, Interoperable and Reusable) data principles is required to give such research data greater value and enhance their propensity for reuse to society's advantage (European Commission, 2018). Food systems microbiome research requires capacity in bioinformatics, which is often misunderstood as an assisting science (De Filippis et al., 2018; Quijada et al., 2020). An important question that arose during the workshop was: How to overcome this challenge? University-based education should clearly distinguish between bioinformatics skills on different levels: user level, developers/high-performance computing/data scientists and bioinformaticians. Nowadays, most life scientists need to use computational methods. User-level skills enable them to design computational experiments and data analysis steps, perform these calculations using published software, and interpret and visualize their results. The developers should be able to evaluate the methods in place, assuring their proper functioning and maintenance, and they should have a solid algorithmic and programming background. Training at this level is usually provided as a master's programme. Lastly, bioinformaticians should have a deep understanding of biological problems and their solutions, the ability to develop new computational methods for new and existing biological problems and be able to work on methodological inventions and complex data integration. Master programmes in bioinformatics can provide training in all aspects of user and developer levels but also educate the students towards a deeper understanding of computational algorithms in biology, their complexity and their statistical and technical background. With decreasing sequencing costs, the size of data sets in microbiome studies and the sequencing depth per sample have increased. This led to studies with higher statistical power, and consequently to the transition of operational taxonomic unit tables and functional profiles from end-goal deliverables into starting material for downstream analyses such as machine learning (ML) applications (Pasolli et al., 2016). Artificial intelligence (AI), ML and deep learning (DL) have been revolutionary for microbiology (Goodswen et al., 2021; Qian et al., 2023). Given the public understanding of and exposure to ML, this seems relevant in the context of deciphering, performing, mapping and manipulating microbiomes in general and in the food systems in particular. Therefore, all these new technologies must also be covered in the bioinformatics Master curricula.

The importance of multidisciplinary applied sciences in food systems microbiome R&D, hands-on training and collaboration between universities and industry must be highlighted. Nowadays, microbiome science is an interdisciplinary research field connected to diverse areas, for example, agriculture, food science, biotechnology, bioeconomy, mathematics (informatics, statistics and modelling), plant pathology and human/veterinary medicine (Olmo et al., 2022). Bioinformatics plays an increasing role in predicting and assessing the desired and undesired effects of microorganisms on food systems

(Garrigues et al., 2013). A combination of bioinformatics with laboratory verification of selected findings is particularly powerful. As an example, bioinformatics methods can be used to improve the microbial production of fermented food products. These include systemic-based functional predictions, the creation of genome-scale metabolic models and the prediction of complex food properties (such as taste and texture) and properties of complex fermentations (Alkema et al., 2016). In terms of education, this is an excellent opportunity because it gives the possibility to students to explore different fields of knowledge; however, it also increases complexity and requests specific skills to be properly addressed. The latter is also relevant when considering the abilities educators should possess. From content-based learning, we are transiting to an experience-based approach, where students learn following innovative educational pathways (Andresen et al., 2000).

Studies on CRISPR-Cas (clustered regularly interspaced short palindromic repeats [CRISPRs] and CRISPR-associated [Cas]) underwent exponential evolution, due to the capacity of this molecular tool to perform specific DNA cleavage and its potential in editing genomes. Currently, this tool is applied in various medical, biotechnological, food and agricultural fields (Adli, 2018; Amine et al., 2021). The CRISPR process' ability not to introduce foreign DNA into the genome has enabled the products to be considered non-GMO (genetically modified organism) by many scientific researchers and at least some products developed using this technology will not need to be labelled GMO. Moreover, the application of CRISPR in the food industries is also enormous for improving the results of starter cultures and probiotics, eradicating harmful microorganisms and spoilage pathogens (Amine et al., 2021; Stout et al., 2017). These CRISPR-based new technologies should be introduced during university courses, as it is key for developing new agricultural and industry methods in order to reach an innovative and sustainable food system.

The so-called 'challenge-based learning' (Gallagher & Savage, 2020), which was presented during the workshop, has been attracting interest to address the complexity of certain topics. Students with different backgrounds going from hard to soft science disciplines were put together in groups and asked to address a specific challenge and design a suitable solution. An example of this kind of methodology was the EIT Food (https://www.eitfood.eu/) initiative: 'Microbiome-Push: into the microbiome exploitation in food systems' (https://www.eitfood.eu/projects/microbiome-push-into-the-microbiome-exploitation-in-food-systems-2020), a project developed in 2020 in which four universities and three companies participated. The project, coordinated by the University of Torino (Italy), aimed at exploring the application potentials of microbiomes in different compartments of the food system, from primary production to food transformation, waste valorization and consumer health, by using a challenge-based approach. This represented a very good initiative to put students in contact with the industry and enable them to address microbiome-related challenges, apply their knowledge and acquire new skills in the domain of food systems microbiome. Transversal skills and competencies, such as collaboration, sustainability and innovation, should be commonly integrated into institutional policies and curricula to improve student employability in post-university life. Student-led approaches, such as challenge-based learning, can support this type of skill development and have been identified in higher-level policy and strategy as key to institutional reform, student progression and mobility (Gallagher & Savage, 2020).

INDUSTRY

Microbiome science evolved rapidly over the past two decades and has become a popular topic not only in the scientific community or among the citizens but also in the industry because of the growing demand for microbiome-based technologies and providing value-added solutions (Ferrocino et al., 2023; Sabater et al., 2021; Van den Bogert et al., 2019). Therefore, including industry actors in discussions on educational needs and technological hurdles of food systems microbiome-based innovations is required. Industrial workplaces are evolving rapidly, prompted by the impact of the ever-changing business technologies and other externalities, such as climate change, antibiotic resistance and the COVID-19 pandemic. Thus, managers in the industry are faced with many challenges when it comes to sourcing, recruiting and retaining the best talents. This is particularly true for companies working in the food systems microbiome field. As the industries and niches become more complex, new and more intricate, novel job opportunities arise.

Since the environment, plants, animals and humans are so intricately linked in the food chain, a systems approach is needed to fully understand the potential impacts of any changes. This means that there is a demand for researchers with a diverse range of scientific and communication skills. From basic microbiology (including expertise in traditional and emerging culturing approaches), microbial physiology, design and interpretation of metagenomics and other -omics projects, microbial ecology and the ability to integrate approaches to agricultural and medical science. With the current demand for acceleration, companies will increasingly be looking to streamline manufacture and commercialization. Thus, companies also need individuals that can innovate, by using technology, data and automation, implementing agile methodologies, increasing transparency and with proven levels of problem-solving and collaboration abilities. Individuals with the ability to build and sustain mutually beneficial scientific partnerships, and those that can nurture collaborations across disciplines/sectors both nationally and internationally will be specifically in demand by industry and other organizations.

According to workshop participants, basic microbiome science training programmes need to be widely provided across relevant life science and biotech companies but in a way that is making a positive difference and brings added value to the industry, its customers and the environment (Table 2). The key is to look at the real needs of the targeted industries, to identify the professionals involved in food systems microbiome science and to design a tailored training concept fitted to all needs. A good understanding of the national professional training system is needed, as there is high variability at the level of company culture, national certifications, financing schemes and company-specific prescriptions. As such, all industries might have to work on adequately training their employees, even those not involved in R&D, as well as their partners and customers. This would allow the identification of the most adapted path to target specific professionals at every level and adapted actions throughout professional life (professional colleges, then seminars, professional training or evening courses, etc.).

The impact of academia on industrial success is undeniably high as many of the products in the market and start-up companies originated from academic leads (Olmo et al., 2022; Rasmussen & Wright, 2015). Universities and other public research institutions serve as major sources for trained research employees, novel scientific hypotheses, modes of action and early-stage technologies. However, while researchers in academia hold many keys to technological breakthroughs, they frequently face resource limitations. This is likely to be a result also of research priorities and how the limited resources are invested. Translation of early-stage technologies into profitable products requires investment in research in more advanced stages of the product development process, with a focus on microbial functionalities underlining product definition specifications such as target market efficacies, and commercial viability. Scale-up and field-wide testing raise confidence in technologies and lead to a higher evaluation by the industry, with better chances to reach commercialization. Thus, investing in more applied aspects should lead to better translation of technologies into products. Biotech companies should contribute to public

TABLE 2 Summarized list of main needs and immediate, mid- and long-term actions recommended at different levels of industry and who is responsible for taking what type of action to address these needs elaborated during the workshop.

	Needs	Recommended actions	Who (actors)
Industry	Training collaborators and employees	Collaboration between public research institutions and industry to: • Identify aspects in which microbiomes can affect the industry. • Optimize tools that will be useful to the industry. • Develop trainings adapted to the industry internal needs (budget for education). • Further trainings with academia could accelerate professional knowledge of the microbiome in younger generations.	Companies Academic Public scientific institutions
	Require an increasingly diverse supply of personnel at multiple education levels to expand and meet the opportunities and challenges introduced by emerging technologies and to develop novel assets	Teaching transferable skills required by industry: • Technology use and development: data analysis, IT… • Problem-solving: analytical thinking and innovation, creativity, originality and initiative, critical thinking… • Self-management: active learning and learning strategies, resilience, stress tolerance and flexibility… • Working with people: Leadership and social influence.	Academia Companies
	Private/industry-public funding and research interaction	Trans-sectorial dialogue. The private industry should invest in training and consultation with experts from academia.	Companies Academic Public scientific institutions
	Collaboration between academics and industry to support innovation in the food systems microbiome sectors	Private industry should invest in technology transfer collaborations with academic laboratories	Companies Academic Public scientific institutions

research initiatives to keep up with scientific narratives and technologies that are currently being developed. Furthermore, it would be desirable for these companies to invest in training and consultation with experts from academia and regulators, and in technology transfer collaborations with public research laboratories.

CONCLUSIONS AND FUTURE PERSPECTIVES

Policymakers, regulators, farmers, citizens and other stakeholders should be informed and educated that microbiomes are everywhere and have numerous highly important functions (Berg et al., 2020). This spans from primary school children to curricula that build competencies in scientific and professional communities. Throughout the workshop discussion, it emerged crucial need to integrate basic microbiome-related knowledge into the school curriculum. For that, teachers trained in microbiology are required, and more hands-on options to quickly classify and visualize microbiomes (e.g. by the usage of portable Oxford Nanopore technologies) are needed. Increasing microbiome literacy from childhood must be a key element in microbiome-focused educational agendas.

Scientific institutions, universities and professional societies should consider engaging media consultants to assist them in disseminating scientific advances widely and promptly. They can be an online dynamic display for research projects and publications, allowing an enhancement of the visibility of our science worldwide.

Furthermore, scientists can gain by engaging early on in open, ethical and transparent communication with stakeholders. The aim is to keep people engaged and informed from the earliest stages to come to a win–win for all: (1) Consumers know and trust their food and the technologies that are applied to them (including food safety aspects); (2) citizens know where to go for information and are empowered to make informed choices; (3) farmers and industry understand how to use microbiome applications and use novel products responsibly; (4) regulatory efforts support a sustainable, safe food supply; (5) scientists gain visibility and deliver real-world impact that contributes to tackling global challenges like climate change, malnutrition and unsustainable food chains.

Industry, start-ups and established multinationals are already exploring food systems microbiome innovations. But due to the sheer diversity, number and complexity of microbiomes, it is a challenge to study and analyse them at scale. Policymakers will need to align on terminology, agendas, knowledge sharing and availability of data to develop consistent regulatory frameworks that are innovation-friendly. To support innovation, governments need to step up long-term investment in education, research, production infrastructure, data management systems and biobanking. Future technologies and systemic innovation are critical for the profound transformation the food system needs. The speed of innovation could be significantly increased with the appropriate incentives, regulations and social licence. These, in turn, require constructive stakeholder dialogue and clear transition pathways. Furthermore, government investment is essential to ensuring that research funds are extended to areas that may not have an immediate commercial value but have long-term implications for society. Since the beginning of the new millennium, academics and practitioners have paid increasing attention to AI technologies in operational process management and challenges for new business models, in a sustainable and socially responsible perspective (Di Vaio et al., 2020). There is huge interest in using different AI applications, such as ML models, natural language processing and computer vision to improve food systems (Feucherolles et al., 2022; Goodswen et al., 2021; Qian et al., 2023).

The enhancement of food systems microbiome could accelerate the attainment of the SDGs (Timmis et al., 2017). The SDGs are a group of 17 overall goals aimed at improving life on Earth, specifically to end poverty, protect the planet and ensure prosperity for all and solve the most serious global economic, societal and environmental issues (United Nations, 2015). Microbiomes have a direct link to achieving SDGs addressing food security, health and well-being, clean energy, environmental degradation and climate change (Timmis et al., 2017). The multidisciplinary nature of microbiological research will help in facilitating an integrated approach to answering questions and solving problems raised by the SDGs. In conclusion, microbiome educational programmes could support the attainment of all the goals previously presented in this work (such as building a microbiome-literate society, human, plant, animal and environmental health, preserving microbial diversity, and going hand in hand with SDGs and EU Green Deal) and help foster sustainable innovation to the advantage of all citizens.

AUTHOR CONTRIBUTIONS

Rocío Olmo: Conceptualization (equal); writing – original draft (lead); writing – review and editing (equal). **Stefanie Urimare Wetzels:** Conceptualization (equal); writing – review and editing (equal). **Gabriele Berg:** Writing – review and editing (equal). **Luca Cocolin:** Writing – review and editing (equal). **Moritz Hartmann:** Writing – review and editing (equal). **Marta Hugas:** Writing – review and editing (equal). **Tanja Kostic:** Conceptualization (equal); writing – review and editing (equal). **Thomas Rattei:** Writing – review and editing (equal). **Manfred Ruthsatz:** Writing – review and editing (equal). **Daria Rybakova:** Writing – review and editing (equal). **Angela Sessitsch:** Conceptualization (equal); writing – review and editing

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CONFLICT OF INTEREST STATEMENT

The authors declare no financial or commercial conflict of interest.

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