Deliverable 3.4

Strategic Research and Innovation Agenda for future microbiome activities and applications

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Microbiomesupport.eu – #MicrobiomeSupportEU
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Abbreviations

Partners
AIT: AIT Austrian Institute of Technology
CSIC: Consejo Superior de Investigaciones Cientificas – The Spanish National Research Council
DLR: German Aerospace Centre
FFoQSI: Austrian competence center for Food and Food Quality, Safety and Innovation
HMGU: Helmholtz Zentrum München – German Research Center for Environmental Health
VLO: Department of Economy, Science and Innovation – as part of the Flemish Government
WU: Wageningen University
WR: Wageningen Research
INRAE: French national research institute for agriculture, food and environment

Other abbreviations
AMR: AntiMicrobial Resistance
CAMI: Critical Assessment of Metagenome Interpretation
CSA: Coordination and Support Action
EC: European Commission
EU: European Union
GHG: Greenhouse Gases
MS-CSA: MicrobiomeSupport Coordination and Support Action
R&I: Research and Innovation
SDG: Sustainable Development Goal
SRIA: Strategic Research and Innovation Agenda

1. Executive summaries

'Microorganisms orchestrate life on Earth': such an assertion feels more philosophical than scientific. However, microbial communities – known as microbiomes – are indeed the largest contributors to the Earth's biosphere diversity. Microbiome research has dramatically increased in recent years, yielding a myriad of new insights into microbial communities, their interactions, and effects, both in close association with their host and in larger systems. Beyond the emphasis on human health and well-being, recent evidence has pointed to the potential of microbiomes to address other ongoing challenges, notably those regarding food systems (including soil fertility, plant and animal nutrition and health, food security, waste management) and climate change adaptation and mitigation (including carbon sequestration and greenhouse emissions reduction). With the climate change threat looming and a global population predicted to reach almost 10 billion by 2050, developing a resilient, sustainable, and inclusive food system, in line with the European Commission's (EC) Food 2030 framework, is imperative.

MicrobiomeSupport aimed to bring attention to the microbiome's potential to foster a modern circular economy and a fair and healthy food system. This initiative was aligned with the European Green Deal priorities and Farm to Fork Strategy for a fair, healthy, and environmentally friendly food system, as well as with the EU's climate ambition for 2030 and 2050.

As part of *MicrobiomeSupport*, we have developed a Strategic Research and Innovation Agenda (SRIA) through an open and transparent process based on knowledge sharing, brainstorming sessions, workshops, and a two-round online Delphi survey. This survey was scored by experts in the field and a cross-sectoral community interested in understanding food systems-related microbiomes and harnessing their potential in a sustainability- and bioeconomy-focused approach. This report sets out the entire process undertaken by a large community that has come together and aligned priorities for the benefit of food systems sustainability and the health of the planet and the living beings that contribute to and benefit from food systems, including humans.

This SRIA, which calls for a new systems approach in microbiome research and innovation, is structured around five pillars as potential pathways for transforming the EU food system.

- Pillar 1: Frontier research
- Pillar 2: Capacity building for open microbiome research and innovation
- Pillar 3: Harmonisation of methods and tools
- Pillar 4: Knowledge transfer and innovation in a suitable regulatory framework
- Pillar 5: Public engagement and education

The implementation of this SRIA through the creation of an *International Microbiome Research Consortium* would ensure the best use of microbiomes to develop healthy and sustainable food systems and diets that will contribute to meeting today's global and human challenges in an ethical and inclusive way.

Executive summary for policy-makers

With recent breakthroughs in microbiome research and through new insights into the roles and services of microorganisms, our perception of the living world has changed substantially. Emerging evidence has pointed to the relevance of host–microbiome relationships in the development, production, nutrition, and health of living beings on Earth, as well as the key role of microbial ecosystems in geochemical cycles (carbon, nitrogen, phosphorus) in upgrading side streams, bioremediation, and food safety and security.

Within the *MicrobiomeSupport Coordination and Support Action* (MS-CSA), we proposed embracing a holistic approach to leverage food system microbiomes to enhance sustainability, reduce the environmental footprint, improve food quality for better health of the planet and living beings, and further advance the bioeconomy. With these objectives in mind, an international transdisciplinary working group made efforts to establish the Strategic Research and Innovation Agenda (SRIA) through a transparent and inclusive process. This agenda brings together the European research and innovation horizon (and beyond) around five priority pillars:

- Pillar 1: Frontier research
- Pillar 2: Capacity building for open microbiome research and innovation
- Pillar 3: Harmonisation of methods and tools
- Pillar 4: Knowledge transfer and innovation in a suitable regulatory framework
- Pillar 5: Public engagement and education

Together, these strategic priorities, drawn up by multiple experts and stakeholders, are likely to ensure more effective action and funding. We believe that the implementation of this agenda would fuel microbiome research and innovation, warrant optimal applications of food systems-related microbiomes to support the transition towards a sustainable agri-food sector, support the precepts of a circular economy, and help address today's global and human challenges in an ethical and inclusive fashion. This SRIA also provides the first central and consensual building block towards an *International Microbiome Research Consortium* which could:

- implement this SRIA in all its dimensions;
- be a resource centre available to policy-makers, regulators, and civil society;
- maximise research impact and sustainability through coordination and interactions with end-users;
- enhance sharing and capitalisation on past, current, and future activities as well as results and innovations;

Executive summary for citizens

Microorganisms, invisible to the human eye, are extremely diverse and play a crucial role in the functioning of the planet and the living beings that inhabit it. Our food systems must evolve to meet current challenges such as the mitigation of and adaptation to climate change, rational and respectful use of resources, reduction of chemical inputs such as antibiotics, pesticides, and fertilisers, and preservation of environmental, plant, animal, and human health while ensuring food security.

Microorganisms that live mostly in communities called microbiomes can have a central role in making food systems more sustainable. Microbiome science has progressively revealed the services provided by microbiomes in different contexts. For example, microbiomes often constitute natural barriers to the establishment of infectious pathogens. This observation directs research towards understanding the functions and mechanisms involved and towards innovations based on living organisms aimed at reducing the use of antibiotics in animals and humans and the use of pesticides in crops. However, research must also look at the whole system and how these new practices (such as those used on crops) might affect the rest of the food system, from processing components into feed and food products, to their consumption by animals or humans and the management of by-products and waste.

Within the scope of the *MS-CSA*, European and international scientists have developed a Strategic Research and Innovation Agenda (SRIA) that summarises the activities identified as priorities for microbiome research to fully contribute to the transformation of food systems. This SRIA includes priorities to advance the following areas:

- Frontier research
- Capacity building for open microbiome research and innovation
- Harmonisation of methods and tools
- Knowledge transfer and innovation in a suitable regulatory framework
- Public engagement and education

We are strongly calling for the creation of an *International Microbiome Research Consortium* to promote the implementation of these consensual priorities using a responsible and ethical approach through a co-construction process aimed at integrating all stakeholders, including end-users and civil society.

2. Introduction

Microorganisms – bacteria, archaea, viruses, fungi, single-cell protozoa and algae – are everywhere in the food system. With recent advances in the field, the microbiome has recently been re-defined as a characteristic microbial community and its 'theatre of activity', which includes other microbial structures (like their DNA or metabolites) under specific environmental conditions. The microbiome forms a dynamic and interactive microecosystem prone to change in time and scale, and it is integrated into macroecosystems, which include eukaryotic hosts. The inclusion of the host provides a broader view on the ecosystem where bidirectional microbiome–host interactions influence the characteristics of the microbial environment's 'theatre of activity' [1].

In recent years, greater attention has been focused on the role of microbiome research in addressing societal challenges, specifically the Sustainable Development Goals (SDGs) adopted in 2015 by all United Nations Member States. Microbiome applications could help ensure food and nutrition security, promote sustainable agriculture (SDG 2), health and well-being (SDG 3), clean water and sanitation (SDG 6), food waste management (SDG 12), and adaptation and mitigation to climate change (SDG 13) [2, 3].

At the European level, the Green Deal [4] aims to make Europe climate neutral by 2050. To help meet this target, the EU has agreed to reduce its net greenhouse gas (GHG) emissions by at least 55% by 2030, compared to 1990 levels. This level of ambition requires action in all sectors of the economy, including the agri-food sector, because food systems are estimated to contribute a third of anthropogenic GHG emissions [5]. In addition, research and innovation (R&I) are recognised as key drivers in accelerating this transition.

Food 2030 [6] is the EU's R&I policy aiming to transform food systems to ensure everyone has enough affordable and nutritious food to lead a healthy life. Microbiome research is one of the pathways for action identified in the Food 2030 agenda to help the EU achieve the Green Deal objectives. Microbiome research and innovation can deliver concrete benefits for nutrition, climate, circularity, and innovation in order to shape sustainable food systems.

The Farm to Fork Strategy [7] is at the heart of the European Green Deal and aims to accelerate the transition to a sustainable, healthy, and environmentally friendly food system. In this context, a key area of research relates to microbiomes not only as a lever to reduce dependency on pesticides, fertilisers, and antimicrobials in food and feed production but also as a way to stimulate sustainable food processing, the production of safe foods, and a shift to healthy diets while reducing food loss and waste.

In addition, the circular biobased economy is still a largely untapped domain where microbiome applications can play an important role. For instance, the EU Bioeconomy strategy for a sustainable Europe [8] – which aims to reduce dependence on natural resources, transform manufacturing, promote sustainable production of renewable resources from the land, fisheries, and aquaculture and their conversion into food, feed, fibre, biobased products, and bioenergy – recognises that the benefits from biodiversity-rich ecosystems could be better integrated in primary production through specific support to the development of microbiome-based solutions in value chains.

Considering the existing policy context, the *MS-CSA* project has endorsed the concept of the food systems approach for microbiome research. It encourages future initiatives to use a systems approach covering the whole production chain and to work in an interdisciplinary and transdisciplinary way to understand the role of microbiomes in different ecosystems and assess how microbiomes are interconnected throughout ecosystems [8].

3. A transparent, open, and multi-sectoral approach

The *MicrobiomeSupport* SRIA is the output of a transparent process encompassing the collection of inputs from a wide range of sources, including literature, scientific strategy documents, and brainstorming sessions during *MicrobiomeSupport* events and workshops (Figure 1).

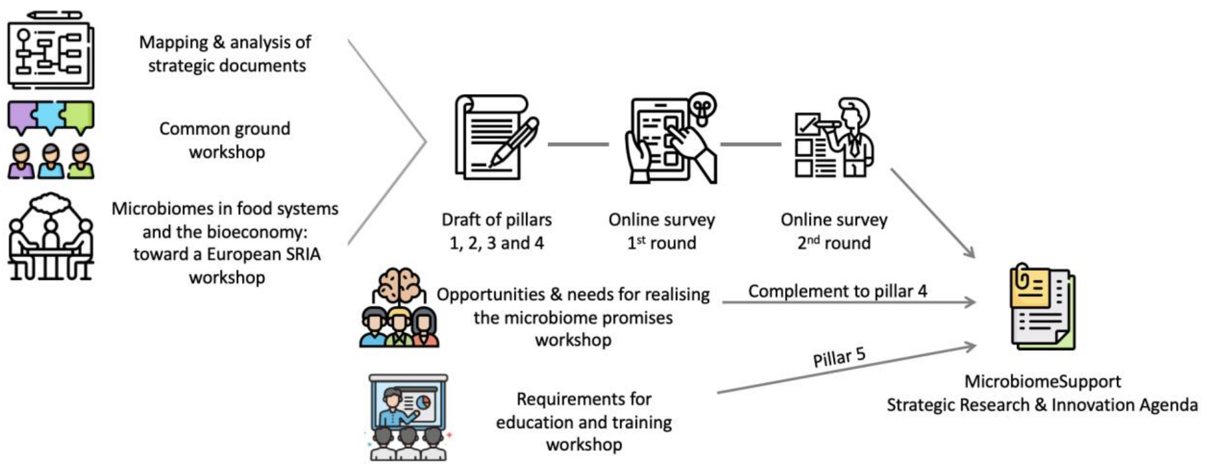

Figure 1. Main contributions of *MicrobiomeSupport* activities and events to the Strategic Research and Innovation Agenda

The mapping, coordinated by WR and involving all project partners and associated stakeholders, was complemented by a bibliographic analysis to study the microbiome landscape. This analysis clearly highlighted the fragmentation of the R&I area and called for a holistic approach to connect different ecosystems. The limited size of most funded projects and the low profile of the microbiome in research strategies published before 2020 are possible explanations [8].

The Common Ground Workshop organised in Vienna (March 2019) included brainstorming, sectoral sessions focused on the microbiome research and innovation landscape in the last five years. Furthermore, a visioning session focused on the expectations, the most important barriers, and the planned contributions of the *MS-CSA* project, partners, and stakeholders. The collected information was further used to organise a workshop entitled *Microbiomes in food system and the bioeconomy: toward a European strategic research and innovation agenda for food systems microbiome* in Brussels (March 2020), to consolidate the work and continue the analysis and visioning process by:

- identifying measures to mitigate the existing barriers and reach the *MicrobiomeSupport* vision for 2030;
- determining the 'building blocks' required in the SRIA.

As a result, the gaps analysis was consolidated and pathways to fill the gaps were identified. Altogether, the process made it possible to draft the five pillars of this SRIA.

Building on all these outcomes and the delineation of research needs, preparatory work for a Delphi survey was undertaken. A two-round online Delphi survey was then scored by researchers, industry representatives, policy-makers, and other interested stakeholders. These consultations were carried out in March and December 2021, and a total of 200 replies were received from 33 countries (Figure 2). The survey was organised into five key scientific areas (Biodiversity, Primary Production, Food Safety and Quality, Human Health, Healthy Planet) and five transversal areas (Infrastructures, Reference Materials and Standardisation, Data Access and Sharing, Knowledge Transfer, Society Awareness) that R&I policy should consider in future strategic planning processes. The first round of consultation aimed to collect feedback on key challenges and objectives to be set out in the SRIA. The feedback from this consultation was then used to refine the thematic areas and transversal issues, addressed in a second consultation round targeting different stakeholders/audiences. A high level of agreement (88.3%, Figure 2) was reached, reflecting a strong consensus on this SRIA and its priorities.

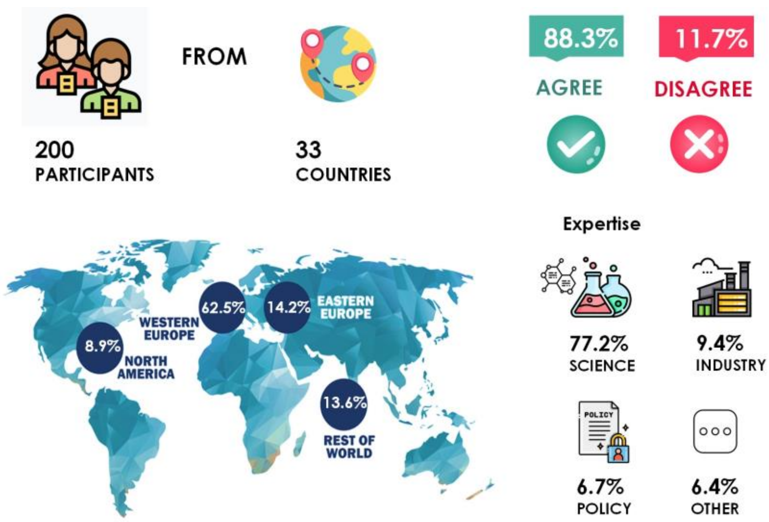

Figure 2. Delphi survey, overview of participants origins, domain of expertise and level of agreement

We also integrated the outputs from two dedicated workshops to complement SRIA pillar 4 on matching the innovation potential and the regulatory framework and pillar 5 on educational needs.

It is important, particularly for fast-growing scientific fields, to consider the regulatory frameworks that apply to the approval of emerging and future innovations. To address this aspect, CSIC, together with other *MS-CSA* task contributors, organised a trans-sectoral workshop entitled *Opportunities and needs for realising the microbiome promises* (November 2020) to round off the analysis by bringing together innovation and regulation experts. This workshop sought to (i) showcase the potential of microbiomes to build a robust bioeconomy, (ii) generate a realistic context for the implementation of microbiome research agendas, enabling innovation for safer and sustainable food production systems and human and environmental health, and thus contributing to the achievement of key SDGs, and (iii) reflect on how to integrate regulatory aspects into the *MicrobiomeSupport* SRIA to facilitate and stimulate the translation of microbiome science into applications to bring solutions to society and the bioeconomy.

The development and implementation of future microbiome applications in the food and bioeconomy sectors will require well-educated employees being trained in microbiome-related technologies (e.g., -omics, bioinformatics) and other multi-disciplinary aspects. To elucidate microbiome-related educational needs in food systems, FFoQSI and other *MS-CSA* task contributors organised a workshop entitled *Educational Needs* (November 2021) that brought together company representatives (from the Industry Advisory Group), public health authorities (from the Funding & Policy Advisory Group), and science and global university representatives (from the partners and the Expert Pool).

4. The *MicrobiomeSupport* Strategic Research and Innovation Agenda

The SRIA is composed of five interconnected pillars (Figure 3):

- Pillar 1: Frontier research
- Pillar 2: Capacity building for open microbiome research and innovation
- Pillar 3: Harmonisation of methods and tools
- Pillar 4: Knowledge transfer and innovation in a suitable regulatory framework
- Pillar 5: Public engagement and education

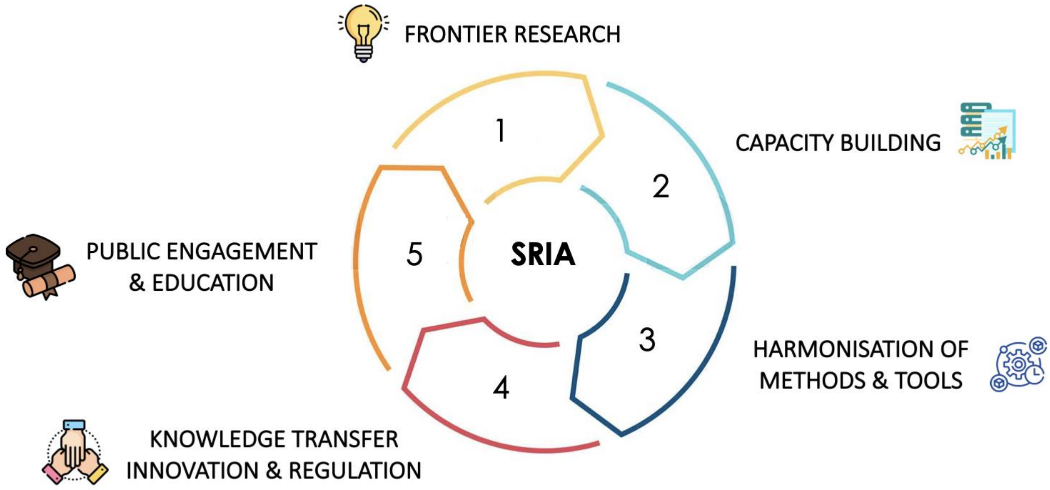

Figure 3. Five interconnected pillars of the *MicrobiomeSupport* SRIA

4.1. Pillar 1: Frontier research

This pillar brings together research priorities at the current frontiers of knowledge. This pillar is divided into five interconnected areas that cover different issues associated with the food system.

Microbiome diversity in agri-food systems

Microbial biodiversity is of prime importance for the functioning of ecosystems. Microbiomes exist within and on humans, animals, and plants in both terrestrial and aquatic environments. They form an integral part of our food system and are vital to maintaining its healthy functioning. Microbial communities can influence key parameters of the food system, such as soil health, plant productivity, and animal and human health. Maintaining soil- and host-associated microbial biodiversity holds potentially direct economic benefits for many sectors. This biodiversity is crucial for safeguarding EU and global food security, nutrition, and diet quality. It is the ultimate source of food variety, underpins the ecosystem services that sustain life and is an integral determinant of health.

To foster advances in microbiome-related research for safer, healthier, and more environmentally friendly food systems, we need better characterisation of microbial diversity (structures, functions, metabolites) in food systems, taking into account spatiotemporal dynamics and agri-food practices. Also, tracking changes in the microbiome over time may provide the foundation for developing new solutions and easy-to-use tools/markers to assess and monitor biodiversity at critical stages and ensure food system sustainability.

Given the multi-functional nature of food systems, a further step should include modelling and predicting microbiome interactions in the food system and their consequences on food system management. The characterisation of such interactions (including microbial transfer/flows) between multiple stages of the food system (e.g., soil, plant production, processing of plants into feed and food) would help better assess the risks and benefits of microbial diversity and determine critical steps resulting in greater health risks. This would enable a better understanding of the relationships between health risks, microbiome diversity, and resilience. It is equally important to pinpoint potential factors that may influence microbiome diversity (structure/functions) either positively or negatively. More specifically, identifying predictive markers based on microbial diversity could help risk management in food systems. This requires the development of new approaches and interventions based on ecological engineering to mitigate risk and ensure sustainable, resilient, and healthy food systems. Another goal would comprise unlocking the functional diversity of food microbiomes to help develop innovative applications in the food system, such as novel foods or new antimicrobials. Changes in agri-food practices and microbiome-based interventions are poised to influence microbiome diversity and, thus, the sustainability of food systems. To that end, tools such as mathematical models are key to predicting/assessing their impact along the food system chain. Leveraging such models in more translational research related to microbiomes would strengthen our ability to extract meaningful biological data and provide deep insights into microbial communities. Ultimately, a European observatory of microbial diversity would constitute an asset to unlock the potential of microbial innovation.

In addition to supporting the European Farm to Fork Strategy, providing relevant solutions to the emergence of antimicrobial resistance (AMR) in the food system is an additional priority. Tackling the challenge of AMR in the One Health approach requires considering the multidirectional flows of microbial diversity across the food system. In this respect, harnessing the diversity, resilience, and functions of the microbiome would likely uncover the drivers of these flows and eventually lead to the development and implementation of alternative strategies (i.e. prebiotics) to reduce the use of current antimicrobials in food systems.

KEY TARGET: Understand, monitor and leverage diversity as a potential biomarker of healthy systems.

- GOAL 1: Perform systemic and extensive characterisation of microbial diversity and functionality.
    - Identify geographical/temporal changes (in connection with resource variation).
- GOAL 2: Develop traceability, detection and sensor tools.

KEY TARGET: Model and predict microbiome interactions in the food system and their impacts on food system management.

- GOAL 1: Understand interactions between microorganisms as well as those between microbiomes and their host.

- GOAL 2: Develop methods for analysing and modelling microbiome communities.
    - Consider designing functional consortia using systematic characterisation and modelling of microorganisms.
    - Systemic ecology approaches at the food system scale.

KEY TARGET: Harness unknown functional diversity.

- GOAL 1: Comprehensively characterise functional diversity.
    - Advance knowledge on currently unknown functions and their roles in microbiomes, including interactions with the environment, food matrices and hosts
    - Make use of these functions in food systems for more sustainability through biotechnology, new processes for better use of resources and by-products side streams

KEY TARGET: AMR, pathogen flow, microbiome dynamics and their interrelationships.

- GOAL 1: Contribute to reducing AMR in food systems.
    - Understand the impact of drug use, including antimicrobials, on resistance emergence and microbial dynamics in food systems.
    - Understand the mechanisms underpinning the spread of AMR in the environment and between livestock, poultry, aquatic animals, and humans to develop strategies for mitigating this spread.
- GOAL 2: Develop alternatives to current antimicrobials.
    - Discover new antimicrobial drugs or antimicrobial strategies derived from microbiomes that can potentially replace drugs that are no longer effective or potentiate the action of effective drugs to allow for lower doses.
    - Develop novel microbiome-altering therapeutics to block colonisation by resistant microorganisms or treat refractory infections.

Microbiomes to boost sustainable primary food and feed production

Primary production is a prime prerequisite for food and nutrition security, but at the same time, it has a significant impact on the food system's sustainability. Transitioning to a more sustainable agricultural system could deliver a number of economic, environmental, and health benefits. For example, for farmers, who are the backbone of food systems and the frontline managers of natural resources, improved knowledge and use of microbial products would enhance plant and animal health and well-being, prevent interspecies disease transmission and reduce dependency on pesticides and antimicrobials. This would help to reverse the loss of biodiversity and soil fertility while ensuring resilient primary production.

Recent advances in the microbiome field combined with precision agriculture have led to the development of new strategies aiming to reduce the environmental footprint of agriculture and improve public health. This has spurred the development of biological products, such as biopesticides and biofertilisers, with the ability to at least partially replace their synthetic counterparts, controlling the burden of disease and the emergence of antimicrobial resistance while maintaining productivity and competitiveness. They may influence soil fertility and productivity, crop and animal production, and enhance carbon sequestration.

From this perspective, the present thematic area will focus on exploring how microbiomes would influence soil, plant, and animal health.

Soil is one of the most complex ecosystems. It is a habitat in its own right, and home to an incredible diversity of organisms that regulate and control key ecosystem services such as soil fertility, nutrient cycling, and carbon sequestration. Unravelling the complexity of soil microbiomes and better understanding the interactions occurring within such ecosystems are essential to speeding up the transition to sustainable and healthy agriculture by unlocking the potential of microbiomes. Understanding how agricultural practices and amendments (manures, organic or synthetic chemical treatments) influence the soil microbiome is also relevant to identifying factors that maintain soil quality and those that may interfere with the production of healthy food and feed. Since microbiomes contain the seed bank of microbiomes associated and beneficially interacting with plants, gaining insights into the structures, functions, and interactions of soil microbiome communities between these plants/crops and soils is required. Furthermore, a better understanding on plant mechanisms interacting efficiently with microbiomes will lead to the development of plant varieties requiring less fertilizer or pesticide input. Thus, a deeper understanding of soil microbial ecosystems on a global scale would be a prerequisite for the development of innovative microbiome-based products, including markers of expected functionalities/services and associated diagnostic tests, as well as soil remediation or restoration solutions. Further advances in soil and plant microbiome research are likely to foster the development of microbial strategies aiming at improving plant and soil resilience to biotic and abiotic stresses, maintaining soil diversity, and supporting carbon capture and storage, with exciting opportunities for climate change mitigation.

Mapping plant-associated microbiomes at different growth stages, across diverse varieties, and in different geographic areas will help to correlate microbiome diversity and variability to plant yields and health under various environmental and climate conditions. Advanced research on the mechanisms of plant–microbiome interactions and the effects on yield, nutrient acquisition, stress tolerance, and product quality for feed and food purposes will facilitate effective knowledge and data generation and translation into reliable agricultural practices. These will ultimately contribute to crop adaptation to climate change, synthetic pesticide reduction, and improved nutrient cycling. Furthermore, gaining such knowledge will strengthen the expertise in Member

States for the regulatory assessment of microbial applications, such as biopesticides, biofertilisers, and biostimulants, that are essential components of the transition to the European Green Deal.

Of equal importance is establishing causal inferences and gaining mechanistic insights into plant-microbiome interactions and their effects on yield, nutrient acquisition, stress tolerance, food, and feed quality that could enhance plant health and productivity. At the same time, this knowledge will contribute to the sustainability of primary production systems. Likewise, adopting science-based sustainable practices favouring microbiome functions that contribute to plant health and the quality of plant-derived foods and feeds are key to improving plant productivity and health.

Microbiomes, microbiome-related services, and microbial interactions would thus need to be implemented in plant breeding schemes/processes. One should note that novel microbiome-based applications should be coupled with convenient agricultural practices (using biofertilisers, for instance, in line with the European Green Deal). Furthermore, targeted studies are required to identify and validate microorganisms and microbial consortia that influence specific plant traits. This would be a leap in producing fit-for-purpose plants with minimised resource loss by targeting not only soil quality and resilience and plant production and health, but also animal welfare through the development of microbiome-enhanced feed products, supplements and alternative feeds with a low environmental footprint. In a nutshell, targeted studies would ensure resilient primary production, contribute to climate neutrality, and support the transition to climate- and environmentally friendly and resilient agricultural systems.

Animal breeding practices, particularly in young animals, that are known to influence the diversity and functionality of the microbiome with possible consequences on animal performance and health are equally relevant. This could potentially enhance disease resistance through prevention or contribute to the treatment of infectious diseases. It could contribute to the mitigation of GHG emissions as well, e.g., through the production of cattle breeding lines, which harbour microbial communities with low methane emissions while maintaining animal productivity and health. Longitudinal studies are therefore needed to decipher the effects of animal and fish husbandry practices on (i) animal microbiomes and their relationships with productivity, nutritional quality of derived foods, AMR and health outcomes and (ii) the environment.

Since interventions targeting animal microbiomes could rely on the use of feeds, feed ingredients including prebiotics and probiotics, or even crops developed with the goal of modifying the gut microbiome in livestock, it seems likely that the modulation of these microbiomes will improve digestibility and animal production. Therefore, assessing the specific and synergistic effects of probiotics on the diversity of the microbiome in animals is needed. Other aspects include antibiotic resistance, which is a key factor in animal husbandry. There is a need to adopt holistic approaches and develop alternatives to human health-related antimicrobials and methods that limit the impact of antibiotics on the microbiome and the environment. This would require a focus on the microbial ecology of animals, which will lead to a better understanding of antibiotic resistance and its spread in food systems and the environment.

KEY TARGET: Soil quality and resilience.

- GOAL 1: Advance knowledge of complex microbiomes in agricultural soils to determine the most appropriate crop/variety and management practices for the site (phytobiomes approach).
- GOAL 2: Understand interactions between soil microorganisms and with their environment, including various hosts.
- GOAL 3: Explore current crops and understand the rhizospheres of resistant and high-yielding crops to accelerate the development and use of these crops.
- GOAL 4: Understand the impacts of soil amendments to gain insight into practices that can reduce AMR.

KEY TARGET: Plant productivity and health.

- GOAL 1: Explore individual microorganisms, microbiomes (including reconstituted 'synthetic' consortia) and their interactions in agriculturally relevant systems to improve food, feed, and fibre production.
- GOAL 2: Understand the signalling pathways between microorganisms and plants (at different scales and during the development) and how such interactions could contribute to plant performance, health, and productivity.
- GOAL 3: Assess the impact of management practices on soil, plant microbiomes, and plants.
- GOAL 4: Leverage microbiomes to better use and preserve important structural resources for plant development.
- GOAL 5: Develop rational microbiome applications that improve plant production and health and respect ethical principles.

KEY TARGET: Animal production and health.

- GOAL 1: Understand animal–microbiome symbiosis and its impact on health.
- GOAL 2: Establish interventions that modulate animal microbiomes (consider pre-, pro-, synbiotics, etc.) to improve disease resistance, prevent/treat infectious diseases, reduce methane production, and promote efficient and healthy growth.
- GOAL 3: Evaluate the impact of breeding practices and microbial and chemical exposures, particularly in young animals, on microbiome diversity and functionality.
- GOAL 4: Investigate the microbial ecology of animals to decipher the mechanisms that promote antimicrobial resistance.
- GOAL 5: Implement One Health approaches coupled with sustainable agricultural principles and develop participatory approaches to address potential changes in animal husbandry practices that improve the prevention of animal diseases and reduce the use of

antimicrobials, while ensuring their rational use and limiting the negative health and socio-economic impacts on livestock farmers' livelihoods.

KEY TARGET: Leverage microbiomes to improve feed.

- GOAL 1: Leverage microbiomes and microbiomes' functions at all stages of feed production and processing to reduce chemical inputs and residues.
- GOAL 2: Exploit microbiomes (microorganisms, functions, products) to optimise the use of by-products from the food system, particularly in animal feed, and to improve the nutritional quality of feed products.

Microbiome contribution to quality and safety of feed and food products

Advances in microbiome science are expected to provide data and tools for traceability and assessment of food authenticity, leveraging systematic authentication of the microbiome and its variations along the food system, improving food safety, as well as offering protection against spoilage organisms. This is likely to yield innovative food products at different scales, from home to industry, and meet consumers' expectations for transparency and environmentally-friendly foods (certified 'clean' foods).

With increased research on feed and food microbiomes and rapid technological advances, significant insights have been gained on the landscape of food microbiomes and their potential as new biomarkers for food authentication and traceability.

In this regard, the integration of scattered knowledge and the creation of a reference database seem paramount to leverage diversity and variability of feed and food microbial communities and enable the development of new traceability and authentication systems across the food chain. Therefore, implementing quick microbiome analysis tools for screening and validating microbiome-based biomarkers will be required. This would provide useful data on the origin of food products, which would help ensure traceability, control certifications, meet market demand, and limit fraud.

The characterisation of microbiomes of feed and food and their interactions with the environment (notably feed or food matrices) can also help capture multiple interactions between different components of the food system, which could benefit feed and food safety and quality.

Microbial control and management can reduce sanitary issues and economic losses. In particular, the detection of pathogens at all stages of food systems is key for limiting the emergence of foodborne diseases that account for 600 million cases and cause 420,000 deaths each year [9]. These actions would promote resource-efficient food systems from a bioeconomy perspective.

Here, the adoption of -omics approaches as a common tool in food safety has the potential to improve our ability to (i) rapidly harness food microbiomes to detect and identify foodborne pathogens, and (ii) enhance risk management by limiting their presence in final food products.

The development of faster, less computationally intensive, and easier-to-use bioinformatics tools will also play a critical role in facilitating the use of -omics tools. In that regard, the establishment of appropriate regulatory frameworks on the use of -omics data and results will also be important to facilitate industry and government use of these tools. While ecological bioengineering may not be considered an '-omics' technique per se, the tools associated with this discipline can be developed as new microbiome-based solutions and improve risk management as well. This will require a comprehensive analysis of the ability of microbiomes to protect or stimulate protective mechanisms of plants and animals against pathogens.

KEY TARGET: Traceability/origin/authenticity.

- GOAL 1: Characterise microbiomes associated with different types of feed, food, and food systems and identify key actors.
- GOAL 2: Develop microbiome-based indicators for the traceability of food products and their origins.
- GOAL 3: Evaluate the impact of practices on feed and food microbiome diversity and food quality.

KEY TARGET: Safety and preservation.

- GOAL 1: Investigate feed and food microbiomes for pathogen detection. Identify critical stages of contamination and develop risk mitigation approaches possibly based on microbiome applications (diagnostic tools included).
- GOAL 2: Assess the safety of antimicrobial drug residues and pesticides in feed and food and harmonise guidelines used by national and international regulatory agencies to evaluate the effects of plant- and animal-derived foods as part of the risk assessment for humans consuming such chemical residues.

Healthier food for healthier humans: the food–microbiomes–human nexus

Enhancing knowledge on food system microbiomes and the interplay between food compounds, humans and their associated microbiomes would help to enhance lifelong health and limit the dramatic surge of non-communicable chronic diseases.

Symbiotic microbial communities, hosted at various sites within our bodies, have been increasingly appreciated as a dynamic network that contributes to the development and maintenance of our health throughout our lifetimes. The disruption of this symbiosis has been associated with a wide range of diseases and is considered a leading factor in the dramatic increase of chronic disorders. Diet is one important means to shape microbiomes. The increased intake of highly processed foods and regular exposure to xenobiotics through food and water – all typical in western lifestyles – are likely to compromise human health, particularly by disrupting the microbiome–host symbiosis. Meanwhile, other dietary compounds, such as prebiotics [6] or probiotics [7] (naturally found in fermented food), and healthy diets can potentially preserve health and help restore altered symbiosis.

At present, a mechanistic understanding of the host–microbiome relationship is still lacking, and there is a need for more research to gain new and deeper insights into what constitutes healthy human microbiomes and pin down their features. This would help identify 'at-risk' microbiome–host symbiosis and establish microbiome-based biomarkers (taxa, genes, activities, and metabolites that may be relatively increased/depleted in the disease state) for monitoring symbiosis states and predicting disease, while considering interindividual variability and lifestyle. There is also a major interest in setting minimum standards and guidelines to reach a consensus on methods and references for assessing the effect of foods, food compounds, and diets on the microbiome–host symbiosis. As such, efforts must be focused on evaluating the beneficial or detrimental effects of food and water as potential vectors of contaminants or constituents impacting microbiome–host symbiosis and, consequently, health. To this end, prospective longitudinal studies linking the gut microbial ecosystem with the environment (such as, but not limited to, diet) are needed.

Food produced by microbial fermentation also needs further investigation as it currently accounts for 5% to 40% of dietary patterns in given populations [8]. The health benefits of fermented foods have been acknowledged for centuries and stem from the presence of living microorganisms and the fermentation-associated modifications to the food product's ingredients. Fermented foods could shape the composition of the gut microbiota and promote health-promoting metabolites. More research will help develop sustainable dietary strategies based on microbial fermented foods, aiming at improving human health.

An establishment of an open-source platform on the complex interplay between food or food compounds and the microbiome–host symbiosis will be fundamental to support the decision-making process of industries, innovators, and regulatory agencies.

Key areas of research should also include the definition of strategies for the design of precision/personalised food products and diets. The latter needs to be further developed to maintain the microbiome–host symbiosis, preserve health and prevent disease. This would be particularly relevant for people at risk of chronic diseases and patients undergoing treatments as part of their medical therapy to optimise the therapeutic action and avoid adverse side effects affecting human microbiomes. More emphasis should be placed on evidence-based, innovative products that preserve microbiome-host symbiosis and sustain healthy microbiomes at different life stages, thus having a significant potential for use in personalised nutrition.

Current barriers and lock-ins in translating and implementing precision diets include a significant lack of standards and comprehensive studies, and challenging regulatory restrictions. Consumers need an evidence-based framework to make informed decisions. Wider consideration should be given to how these precision food products can be applied and harmonised from a regulatory perspective.

KEY TARGETS: Food, microbiomes, and personalised nutrition for health.

- GOAL 1: Explore, characterise, and understand food functionality for health and develop strategies to identify bioactive compounds that will lead to innovative products.
- GOAL 2: Highlight the functions of the human microbiomes (gut and beyond) and functions of the host that could be targets of food/nutrition in order to modulate nutritional status and human health.
    - Develop personalised solutions to prevent or contribute to treatment of non-communicable chronic diseases.
- GOAL 3: Evaluate the effect of fermented foods on the human gut microbiome and on health parameters that are key to supporting a healthy microbiome-host symbiosis.
- GOAL 4: Understand mechanisms of interactions between fermented foods, different types of food microbiomes and human microbiomes to address the role of fermented foods in nutrition, health, and diet diversity.

Expanding the potential of food system microbiomes for a healthy planet

Climate change is probably the greatest challenge we face today and in the future. Reducing the environmental footprint of food systems is important for mitigating climate change [10] and setting the conditions for a healthier planet [11]. Limiting food systems' unused by-products and waste and promoting resource recycling are crucial to enhance food systems' sustainability. Microbiomes are omnipresent in the food system, making them drivers of sustainability and circularity.

Understanding the functioning of microbiomes and developing ecological engineering to optimise microbial processing of complex substrates, such as agriculture residues, are key to developing biobased innovations. This knowledge would allow the safe upscaling of residues and waste streams from agriculture and animal farming (including aquaculture) and reduce food waste and resource losses.

The impact of current food preservation procedures on food pathogens, spoilage microorganisms, and microbiomes needs to be thoroughly assessed and optimised under different production and processing practices. As a result, the shelf-life for safe consumption will likely need to be reconsidered. Note that this task remains particularly challenging and requires more research and communication on benefit scenarios. Likewise, knowledge on food microbiomes must be leveraged to deliver innovative solutions, including synthetic (microbial) ecology-based approaches, to reduce food loss and waste across all parts of the food systems – from farm to fork. This would engage a wide range of stakeholders, including academia, policy-makers, legislators, industry, and consumers, and offer co-benefits for both circularity and communities.

Of great significance is the prediction of climate change's impact on food system microbiomes and the anticipation of necessary adaptation to these new conditions while still maintaining their performance and safety.

Production of feed for livestock and aquaculture often competes for resources with food production. Upgrading or upcycling side streams and by-products from food systems could alleviate this competition and increase the current global food supply by up to 13% on average, as recently estimated [12]. The functions, metabolic pathways and enzymes present in microbiomes can contribute to this virtuous process by improving non-food-competing feedstuffs. For example, microbial activities can transform by-products by making them more digestible, enrich them with essential compounds such as vitamins, or provide beneficial functions such as pre- or probiotic effects. This emerging area of the biobased economy needs to be strengthened and the microbial potential fully utilised.

Recycling and upgrading food system waste and by-products, including wastewater, is poised to improve circularity and resource preservation. The development of high-value products, including food, feed, and ingredients, from food system waste and by-products using microbiome functions and engineering must be further explored. A closely related theme promoted by the European Commission is the 'bioeconomy', defined as the production of renewable biological resources and the conversion of these resources and waste streams into value-added products [13]. This definition would cover food, feed, biobased products and bioenergy, and naturally includes ways to process food waste. Innovative and effective microbial-based solutions therefore need to be developed (e.g., to improve wastewater treatment, with more consideration of chemical residues and the fate of sludge).

Developing such solutions would (i) entail a systemic analysis of the problems/challenges to better understand where the hotspots for action are, (ii) require social acceptance/investment, and (iii) require adapting current regulations to the new technologies created.

Advances in our understanding of environmental microbiomes (e.g. soil, marine, and fisheries microbiomes) and their functions are essential to uncover enzymes that would be useful for the conversion of natural materials into renewable energy sources and bioproduct components. A key area of research will relate to the development of microbial/microbiome-based feeds as well as food products, supplements, or alternatives that may reduce the environmental footprint and increase the nutritional value of low-cost feeds and foods. This will help address policy objectives of the Green Deal and Farm to Fork Strategy as well as energy security, and will likely accelerate the transition to sustainable food systems.

KEY TARGET: Climate change mitigation and adaptation.

- GOAL 1: Understand, monitor and optimise carbon and nitrogen fluxes through microbiomes.
- GOAL 2: Identify and develop solutions to mitigate GHG production through microbiome engineering and the production of cattle lines sheltering communities with low methane emissions without affecting animal productivity and health.
- GOAL 3: Develop microbial alternatives to meat that would lower dietary carbon footprints.
- GOAL 4: Investigate the microbiome composition and functions in approaches based on the reuse of the waste of nitrogen from wastewater to manage GHG emissions and optimise environmental benefits.
- GOAL 5: Investigate and model the impact of climate change on microbiomes and microbiome services for humans, animals and plants.
- GOAL. 6: Investigate and elucidate key components of wastewater treatment microbiomes to enhance and improve wastewater treatment, particularly for food systems.

KEY TARGET: Upgrade food system side streams and by-products.

- GOAL 1: Identify all by-products that can be processed into non-food-competing feedstuffs and develop microbial processes that allow for optimal valorisation, particularly as novel foods or animal feed, without negatively impacting productivity.

KEY TARGET: Reduce waste and losses.

- GOAL 1: Monitor waste production and leverage microbiomes for efficient remediation processes and the production of high-value compounds and products.
- GOAL 2: Adopt microbial-based strategies for bioremediation of pollutants and detoxification of contaminants.

4.2 Pillar 2: Capacity building for open microbiome research and innovation

Infrastructure for preservation and research on microbiomes

To sustain and fuel research of complex microbiome systems, the development and establishment of suitable supporting infrastructure is crucial. At present, one of the major technological bottlenecks in European (and other) biobank infrastructures is the development of optimised methodologies to preserve complex microbiome systems and assess the success of preservation in terms of maintaining microbiome composition and functionality. Supporting infrastructure needs to be developed to foster the paradigm shift in the scientific approach from the preservation of microorganism-free samples in culture collections and single isolated strains towards maintaining and exploring complex microbial communities.

Biobank infrastructures should have a worldwide focus rather than a strictly European one, and they should join forces with established (national) collections as a backup solution. Relevant examples of pan-European distributed biobank research infrastructures include (i) MIRRI-ERIC, the Microbial Resource Research Infrastructure for the preservation, systematic investigation, provision and valorisation of microbial resources and biodiversity (https://www.mirri.org/), and (ii) BBMRI-ERIC, Biobanking and BioMolecular resources Research Infrastructure European Research Infrastructure Consortium (https://www.bbmri-eric.eu/), which provides expertise and services on a non-economic basis and facilitates access to collections of partner biobanks and biomolecular resources.

Adequate preservation technologies may be complemented with culturomics methods that combine high-throughput isolation approaches with (meta)genomics, transcriptomics or proteomics approaches. Here, the input of recent developments from basic science on how to handle multi-omics data is a major requirement. Furthermore, methods to replicate/multiply complex microbiomes have to be established. Optimised protocols, which fulfil minimum requirements rather than standardised methods, may be the answer to complex microbiome systems. Better harmonisation and open access of methods and protocols as well as the inclusion of detailed metadata (e.g., details on the origin of samples, date, health status) may overcome the lack of reusing samples and existing data [14]. Efforts and adequate preservation techniques must be coordinated to ensure functionality, build up knowledge, train researchers, and make the materials publicly available. Appropriate incentives to make resources available and to cover costs for biobank infrastructures, while maintaining a level of open accessibility, must be considered and put into place. Such infrastructures could also provide high-quality and reproducible reference material, such as mock communities and reference consortia.

There is a consensus among key stakeholders that adequate infrastructure(s) supporting microbiome research need to be established. A selection of representative microbiome samples has to be established, and the challenge of the ownership and accessibility of these samples addressed.

In the context of research infrastructures, sharing of analytical capacities is key. Training for users should be provided at core analysis facilities to give people the skills they need, enable the use of big data, and contribute to increasing standardisation across studies and research programmes.

KEY TARGET: Develop a supporting infrastructure for the preservation of complex microbiome systems at a European level and beyond.

- GOAL 1: Identify synergies and gaps between national collections and establish a research-supporting infrastructure dedicated to ecosystem preservation, culturomics, and screening.
- GOAL 2: Develop optimised preservation and culturomics methodologies for complex microbiome systems.

- GOAL 3: Promote dissemination and harmonisation of good practices (from sampling to storage, propagation, access, and use) and sharing of analytical capacities.

Open-source data and repository platforms

Open-source database gathering information on (food system) microbiomes should be created to improve data reuse. As technology is evolving rapidly in this area, technological solutions should be regularly benchmarked to identify the most relevant support despite the burden of information transfer and new design. These systems need to guarantee good data protection and sufficient storage capacity and must enable rapid and user-friendly access. In addition, these data should be connected with the microbiome resource infrastructures described in the previous section. These databases should be free of charge, easily accessible, and open to users. The format of the stored data, the associated metadata and specific quality control conditions (compatibility) are key aspects that will require an international agreement to enable comparative studies with data from other platforms and repositories. International initiatives (e.g., Critical Assessment of Metagenome Interpretation, CAMI) that test software tools providing minimal requirements are an interesting approach towards reaching a general consensus on the tools' convenience. The model of only accepting articles for publication in scientific journals if the underlying data are deposited in the corresponding data archive is a virtuous practice. A platform of validated analytical tools that are internationally benchmarked and regularly updated along with well-referenced materials would be an asset for leveraging data across the globe, not only for the analysis of -omics-driven datasets but also for mining, analysing and interpreting multi-omics data that require data integration.

KEY TARGET: Develop data storage systems and open-source databases with agreed data-sharing protocols for gathering information.

- GOAL 1: Improve access to and sharing of information through open-source databases gathering information on food microbiomes. Various solutions, such as a cloud-based repository, should be investigated to evaluate their strength in avoiding tedious processes such as downloading information as well as possible weaknesses that might be linked to server locations.

4.3. Pillar 3: Harmonisation of methods and tools

Consensus, accredited or certified reference materials, and minimum requirements ensuring high-quality data and complementing standardised technologies are key to the success of microbial studies. Developing standards for complex systems and standard operating procedures for microbiome research and industrial processes, as well as organising ring tests, is a major challenge. Additionally, transparency, reproducibility, and translation of findings into protocols for data generation (e.g., metagenome, metatranscriptome) and metadata collection along with open access enabling the exchange of reliable data must play a major role in this task.

Efforts to develop robust, long-term, and valid standard operating procedures and standards must be undertaken. New emerging methods, potential risks, and knowledge on a global level should be considered to form the basis for minimum requirements in the field. This double strategy is needed for a fast implementation of new technologies into the existing, well-established pipelines. The necessary infrastructure, technologies and analysis tools should be affordable and accessible. Training avenues for researchers from academia and industry must be established. Networks between academia, industry, and authorities can be an excellent tool to strengthen these standardisation efforts. The creation of an *International Microbiome Research Consortium* could facilitate a co-evolution of the latest technologies and harmonisation of operating procedures and standards and become a resource for an international 'Supervising Microbiome Agency' similar to the ISO.

KEY TARGET: Speed up the development of standard operating procedures and reference materials which can act as global working standards.

- GOAL 1: Develop new methods and reference materials with standard-setting potential.
- GOAL 2: Increase transparency, reproducibility, and translation of findings for protocols for data generation, metadata collection, and open access for data exchange of reliable data.
- GOAL 3: Create an international network/consortium to speed up the harmonisation and co-evolution of technological development and standardisation.

4.4. Pillar 4: Knowledge transfer and innovation in a suitable regulatory framework

Knowledge transfer

A systems approach to R&I – one which brings together inputs from research, primary production (agriculture, aquaculture, and fisheries), harvesting, storage, processing, packing, distribution, waste streams, and consumers – needs to be pursued. Interactions should be fostered between scientists from a wide range of disciplines, from biologists to computational researchers (bioinformaticians) and social scientists, as well as from different sectors: industries, government institutions (including regulatory agencies), producers, food processors, clinicians, and consumers.

Stakeholder engagement beyond academia and industry in R&I projects is key to framing innovation challenges and guiding R&I activities in the desired directions. Cross-disciplinary and cross-sectoral priorities must be established to better understand opportunities, encourage knowledge exchange between different stakeholder groups, co-create, and shape new spaces for industry and 'self-made' products. Both systems-oriented and more specific detailed analyses are needed to overcome knowledge gaps in the value chain.

Harmonised legal frameworks and regulations, international alignment and the establishment of network structures and platforms that address societal issues must move forward in line with increased public awareness and education of the improvements achieved by using microbiomes.

Public-private partnerships are crucial for the successful use of microbiome technologies. A deeper understanding of microbiomes and the development of applications need more efficient knowledge transfer to industry and regulatory agencies. Thus, sector-specific science–industry partnership training models along the food-systems value chain must be established. These training models must be both vocational and sufficiently adaptable to enable a flexible and efficient workforce. Co-creation and involvement of all sectors (industry, agriculture, multiple science and socio-economic disciplines, and regulators) are compulsory for the development of such partnerships and training programmes.

KEY TARGET: To develop cross-disciplinary and cross-sectoral priorities for product development.

- GOAL 1: Set up a food microbiome public–private partnership network that connects the entire food-systems value chain (research communities, primary production [agriculture, aquaculture and fisheries], harvesting, storage, processing, packing, distribution, waste streams, and consumer intake).
- GOAL 2: Scale and speed up product development processes related to microbiome optimisation.
- GOAL 3: Set up science–industry partnership training models focusing on upskilling primary users of microbiome-related manipulation and application techniques.

Co-creating the relevant regulatory framework

As a preamble, it is important to recall the following facts: (i) microbiome science has developed very rapidly over the last decade, mainly in relation to human health but also in different environments, including food systems; this knowledge has generated the need to include a new actor, 'the microbiomes', when considering, for instance, food and chemical safety, plant and animal production, and the health of the planet and its inhabitants; (ii) legislation lags behind science and there is still an absence of explicit legal requirements to account for microbiome-related effects when risks/benefits are considered under the EU General Food Law; (iii) the roadmap for the approval of microbiome-based innovations is particularly complex because microbiome science has been generated in the absence of standards and validated methodologies; developers often lack experience in the regulatory environment and the regulatory path is not always clear for applications in grey or as yet undeveloped areas.

The main conclusions of the workshop are briefly summarised below:

- Microbiome scientists should advance collaboration with regulatory bodies. This would contribute to generating the evidence needed to improve risk assessments and facilitate the approval of microbiome-based innovations intended to promote human, animal, and plant health or to increase sustainability, productivity, safety and nutritional quality of foods.
- There is a need to harmonise best practices and standards for microbiome analysis, from sample collection, storage, and processing to *in-silico* bioinformatics analysis and data interpretation, as well as to identify metrics, biomarkers, or indicators to determine the benefits and risks associated with microbiome changes.
- There is a need to develop methodologies and tiered approaches to systematically assess microbiomes' effects on human, animal, or plant health and food safety.
- Methodologies should undergo international validation through global cooperation actions, for example, with the Organisation for Economic Co-operation and Development (OECD) or the Codex Alimentarius.
- Regulatory assessments must consider paradigm shifts resulting from better knowledge of microbiomes' structure and functioning. For example, the ecological barrier effect against chemicals, additives, or pathogens is often not due to individual strains but to their combination. The assessment of individual strains will not reflect the properties of the whole consortia. The approaches for assessment of the status and overall function of the consortia should be developed.
- Guidelines for assessing microbiome-related effects are poorly developed or simply non-existent in the areas of both food and health (e.g., for aquaculture, biological control agents, live biotherapeutics, or microbiome transfer therapy) while product development is rapidly increasing.
- The gap between scientists and regulators should be bridged by developing a regulatory science curriculum at universities to train researchers in regulatory aspects and regulators in biological sciences.
- A new type of R&I projects should be established involving regulatory science experts in the project from conception and in pre-competitive projects.
- An appropriate policy vision should be developed, and measures that enable the utilization of the microbiome potential should be implemented.

KEY TARGET: Translate microbiome knowledge into safer, productive tools and reliable outcomes.

- GOAL 1: Set up international collaboration to develop best practices and standards for microbiome analysis and interpretation of the results.
- GOAL 2: Identify/develop and validate methodologies and tiered approaches to systematically assess effects related to microbiomes implied in risk–benefit assessments and that are acceptable by regulatory bodies.

- GOAL 3: Develop specific research projects intended to address regulatory questions related to the risks and benefits of microbiome services.

KEY TARGET: Build a microbiomes expert platform to advise regulatory bodies.

- GOAL 1: Contribute to developing regulatory guidelines required to assess the safety and efficacy of microbiome-based products, services, and tools.
- GOAL 2: Monitor microbiome science and innovation to inform policies and legislative gaps and needs in a timely manner.

MicrobiomeSupport has brought together experts from different microbiome domains and contributed through joint work to create a defragmented/cohesive expert body on food systems microbiomes. Representatives from this expert group could act as a standing committee that interacts with regulatory bodies to (i) streamline the identification of relevant experts for the technical analysis of submitted files, (ii) work on shared priorities, and (iii) develop reciprocal knowledge that will be facilitative in the short term. The European Committee on Antimicrobial Susceptibility Testing (EUCAST, https://www.eucast.org/) could serve as an initial model for such a European expert body.

4.5 Pillar 5: Public engagement, awareness and education

Societal awareness

There is a need to improve the awareness of stakeholders and society about the importance and potential of microbiomes within food systems and the bioeconomy as well as in terms of general health and well-being. The aim is to increase the acceptance of new and knowledge-based microbiome applications by involving citizens and stakeholders throughout the whole food system (from primary production to end consumers) in R&I actions. Early, clear, easy-to-understand, and effective communication aimed at the general public is essential.

Communications strategies need to be developed and should actively engage social scientists and humanities specialists, philosophers and creative minds, as well as the public. These strategies should promote scientifically proven approaches/products and explicitly reference universities/ scientific centres. Stakeholder dialogues, creative living labs, national platforms, collaborative models, place-based approaches, training of authorities, and inclusion of microbiomes in early education can be tools to raise awareness and establish tailor-made formats. Given the nature of microbiome research, the hype around microbiomes is a key challenge, but also an opportunity to engage with policy-makers and the public about the importance of microbiome research and microbiology more generally.

KEY TARGET: Improve awareness among stakeholders and society of the importance and potential of microbiomes within food systems and the bioeconomy.

- GOAL 1: Develop collaborative models and initiatives that increase public awareness and spur science–society interaction and education related to the microbiome application potential.
- GOAL 2: Communicate findings and evidence-based potential related to microbiome applications in an objective, informative manner to develop realistic expectations founded on progress in microbiome R&I research.
- GOAL 3: Increase acceptance of new and scientifically-supported microbiome applications by involving citizens in R&I actions.
- GOAL 4: Establish education curricula aimed at the primary and secondary school levels.

Education and training

Key steps enabling food systems to meet food security, nutrition, and sustainability challenges include making the dissemination and communication of research an integral part of research projects. Doing so would (i) enhance the visibility of research outputs, (ii) increase public engagement in science and innovation, which entails broader confidence of society in research, and (ii) likely raise awareness amongst governments and stakeholders on the need to support microbiome research.

Efforts to translate complex science into simpler (but accurate and true) concepts are equally important. Without such attempts, research on the microbiome will remain a very elitist scientific domain and society will never grasp its importance.

The challenge is to instil knowledge about the microbiome from childhood on. Initiatives, such as the International Microbiology Literacy Initiative (IMLI), which aims to provide new materials for teaching microbiology in schools, are instrumental in creating a society that is proficient in key aspects of microbiology. Knowledge-based decision-making at the individual/family level is as important as regional, national, and global policy decisions that affect everyone and the planet.

Likewise, basic training in microbiome science must be widely disseminated across all industries, in a way that makes a positive difference and adds value to the industry itself, its customers, and the environment. Since microbiomes are ubiquitous, comprehensive approaches and discussions with the representative organisations are needed to better understand:

- What does the industry fear? => To help industry players plan for ways to de-risk their projects and train their people on the tools to find solutions.
- What does the industry need? => To adapt and propose training at every level for every type of professional.
- What does the industry envision? => To target research projects to answer some of their questions and then make an effort to integrate curriculum design into these projects to

enable knowledge transfer to professionals in the industry. Support is needed for the development of large European-wide training programmes and curricula.

KEY TARGET: Increase continuous professional education

- GOAL 1: Develop training / new curricula to meet the need of industry, regulatory experts, policy-makers, end-users and professionals.
- GOAL 2: Support networks for the exchange of experiences using microbiomes, such as creative living labs or learning networks.

KEY TARGET: Strengthen the teaching of microbiology in primary and secondary education

- GOAL 1: Teach basic microbiology and microbiome knowledge and foster microbiology skills and understanding.
- GOAL 2: Enrich microbiome literacy and generate updated teaching materials on microbiomes.

KEY TARGET: Refine university and trade education

- GOAL 1: Promote transdisciplinary and interdisciplinary training on food systems and their microbiomes.
- GOAL 2: Adapt training to industry needs and foster trans-sectorial dialogue between companies and academic research and teaching institutions

5. Requirements for implementation

This SRIA highlights a number of challenges and priorities that need to be addressed to realise the potential of microbiomes to transform our food systems toward sustainable development. *MicrobiomeSupport* has brought together experts from different microbiome environments and disciplines that collaborated to create a cohesive agenda for the future R&I activities in food systems microbiomes considering circular bioeconomy concept.

As a next step, a strong recommendation is to build on this dynamic, multi-sectoral expert network to create an International Microbiome Research Consortium which could:

- implement the *MicrobiomeSupport* SRIA in all its dimensions through international actions that would further broaden the range of stakeholders involved in this transparent and inclusive approach, clarify priorities at different scales, from local to global and in different food systems, and map political and financial support;
- be a resource centre, a standing body monitoring microbiome science and innovation available to policy-makers and regulators to, for instance, make it easier to identify experts needed for the technical analysis of submitted files, work on shared priorities, and develop reciprocal knowledge that will be facilitative in the short term;

- coordinate stakeholders and activities to maximise research impact and sustainability, favouring harmonised practices in line with technological developments;
- improve the public awareness on food system microbiomes, develop education and understanding of microbiomes and their applications;
- enhance sharing and capitalisation of activities, results, and innovations of past, current, and future projects.

References

1. Berg, G., Rybakova, D., Fischer, D., Cernava, T., Champomier Vergès, M.-C., Charles, T., Chen, X., Cocolin, L., Eversole, K., Herrero Corral, G., Kazou, M., Kinkel, L., Lange, L., Lima, N., Loy, A., Macklin, J. A., Maguin, E., Mauchline, T., McClure, . . . Schloter, M. (2020). Microbiome definition re-visited: old concepts and new challenges. *Microbiome*, 8(1), 103. https://doi.org/10.1186/s40168-020-00875-0

2. D'Hondt, K., Kostic, T., McDowell, R., Eudes, F., Singh, B. K., Sarkar, S., Markakis, M., Schelkle, B., Maguin, E., & Sessitsch, A. (2021). Microbiome innovations for a sustainable future. *Nature Microbiology*, 6(2), 138–142. https://doi.org/10.1038/s41564-020-00857-w

3. INRAE 2030. *Partageons la science et l'innovation pour un avenir durable.* https://www.inrae.fr/sites/default/files/pdf/INRAE2030-FR.pdf

4. European Commission. (2022, 24 November). *A European Green Deal – Striving to be the first climate-neutral continent*. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

5. Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 2, 198–209. https://doi.org/10.1038/s43016-021-00225-9

6. European Commission. (2020). *FOOD 2030 Pathways for Action. The Microbiome World: A Life Science Opportunity for Our Society and Our Planet.* Luxembourg: Publications Office of the European Union. https://ec.europa.eu/info/sites/default/files/research_and_innovation/research_by_area/documents/ki0220266enn_002.pdf

7. European Commission. (2020). *Farm to Fork Strategy. For a fair, healthy and environmentally-friendly food system.* https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf

8. Meisner, A., Wepner, B., Kostic, T., van Overbeek, L.S., Bunthof, C. J., de Souza, R. S. C., Olivares, M., Sanz, Y., Lange, L., Fischer, D., Sessitsch, A., Smidt, H. (2022). Calling for a systems approach in microbiome research and innovation. *Current Opinion in Biotechnology*, 73, 171–178. https://doi.org/10.1016/j.copbio.2021.08.003

9. WHO. (2021). *WHO Estimates of the Global Burden of Foodborne Diseases.* https://www.who.int/news-room/fact-sheets/detail/noncommunicable-diseases

10. Cavicchioli, R., Ripple, W. J., Timmis, K. N., Azam, F., Bakken, L. R., Baylis, M., Behrenfeld, M. J., Boetius, A., Boyd, P. W., Classen, A. T., Crowther, T. W., Danovaro, R., Foreman, C., Huisman, J., Hutchins, D. A., Jansson, J. K., Karl, D. M., Koskella, B., Welch, D. B. M. . . . Webster, N. S. (2019). Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology*, 17(9), 569–586. https://doi.org/10.1038/s41579-019-0222-5

11. Ritchie, H., Reay, D. S. & Higgins, P. (2018). Potential of meat substitutes for climate change mitigation and improved human health in high-income markets. *Frontiers in Sustainable Food Systems*, 2(16), 1–11. https://doi.org/10.3389/fsufs.2018.00016

12. Sandstrom, M.W., Nowell, L.H., Mahler, B.J., & Van Metre, P.C. (2022). New-generation pesticides are prevalent in California's Central Coast streams. *Science of the Total Environment*, 806(Part 4):150683. https://doi.org/10.1016/j.scitotenv.2021.150683

13. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN

14. Ten Hoopen, P., Finn, R. D., Bongo, L. A., Corre, E., Fosso, B., Meyer, F., Mitchell, A., Pelletier, E., Pesole, G., Santamaria, M., Willassen, N. P., Cochrane, G. (2017). The metagenomic data life-cycle: standards and best practices. *Gigascience*, 6(8), 1–11. https://doi.org/10.1093/gigascience/gix047.