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Defining strategic R&I agendas to enable microbiome applications in food systems and beyond

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Strategic Research and Innovation Agenda

for future microbiome activities and applications



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ABBREVIATIONS



AMR: Antimicrobial Resistance

CSA: Coordination Support Action

EC: European Commission

EU: European Union

GHG: Greenhouse Gases

MS-CSA: MicrobiomeSupport Coordination Support Action

R&I: Research and Innovation

SDG: Sustainable Development Goal

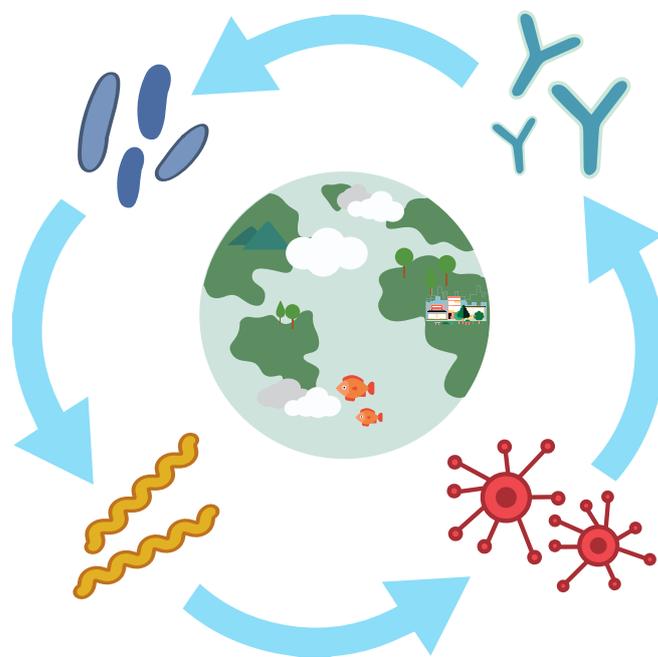
SRIA: Strategic Research and Innovation Agenda

1. Executive summaries

‘Microbes orchestrate life on earth’: such an assertion feels more philosophical than scientific. But 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 spectre of climate change looming and a global population predicted to reach almost 10 billion by 2050 [1], developing a resilient, sustainable, and inclusive food system in line with the European Commission’s (EC) Food 2030 framework is imperative.

MicrobiomeSupport aims to bring attention to the microbiome’s potential in fostering a modern circular economy and a fair and healthy food system. This initiative aligns 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.

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.



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 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.



The implementation of this SRIA through the creation of an International Microbiome Consortium will 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 the field, our perception of the living world has changed substantially as microbiome science continues to unveil new insights into microorganisms' roles and services on the planet and in human activities. 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 Support Action (MS-CSA), we propose embracing a holistic approach to leverage food system microbiomes to enhance sustainability, reduce the environmental footprint, achieve greater food quality for better health of the planet and living beings, and further advance the bioeconomy. With these objectives in mind, efforts so far have included the establishment of a Strategic Research and Innovation Agenda (SRIA) that involved an international transdisciplinary working group through a transparent and inclusive process. This agenda brings together the European research and innovation horizon (and beyond) around five priority pillars:



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 warrant optimal applications of food systems-related microbiomes to support the transition towards a sustainable agri-food sector that would fuel microbiome research and innovation, which is fragmented across disciplines, embrace 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 a first central and consensual building block towards an International Microbiome 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 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 type of 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. To continue with this example, it is clear that research must also look at the whole system and what these new practices (such as those used on crops) might change for the rest of the food system, from processing components into food products to their consumption by animals or humans and the management of co-products and waste.

Within the scope of the MS-CSA, scientists from 33 European countries and beyond have developed a Strategic Research and Innovation Agenda (SRIA) that summarises the activities identified as priorities for microbiomes to fully contribute to the transformation of food systems.

This SRIA includes priorities to advance the following areas:



We are strongly calling for the creation of an International Microbiome 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.

The background of the page is a light blue color with various stylized, darker blue icons of microorganisms scattered throughout. These icons include elongated, wavy forms with cilia, rod-shaped bacteria, and clusters of small spheres. A large, solid blue circle is centered on the page, containing white text.

Microbes
bacteria, archaea, viruses, and fungi
are everywhere in the food system.

2. Introduction

With recent advances in the field, the microbiome concept has recently been defined as a characteristic microbial community and its 'theatre of activity', which includes other microbial structures 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 of the ecosystem where bidirectional microbe–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 to transform food systems and ensure everyone has enough affordable, 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.

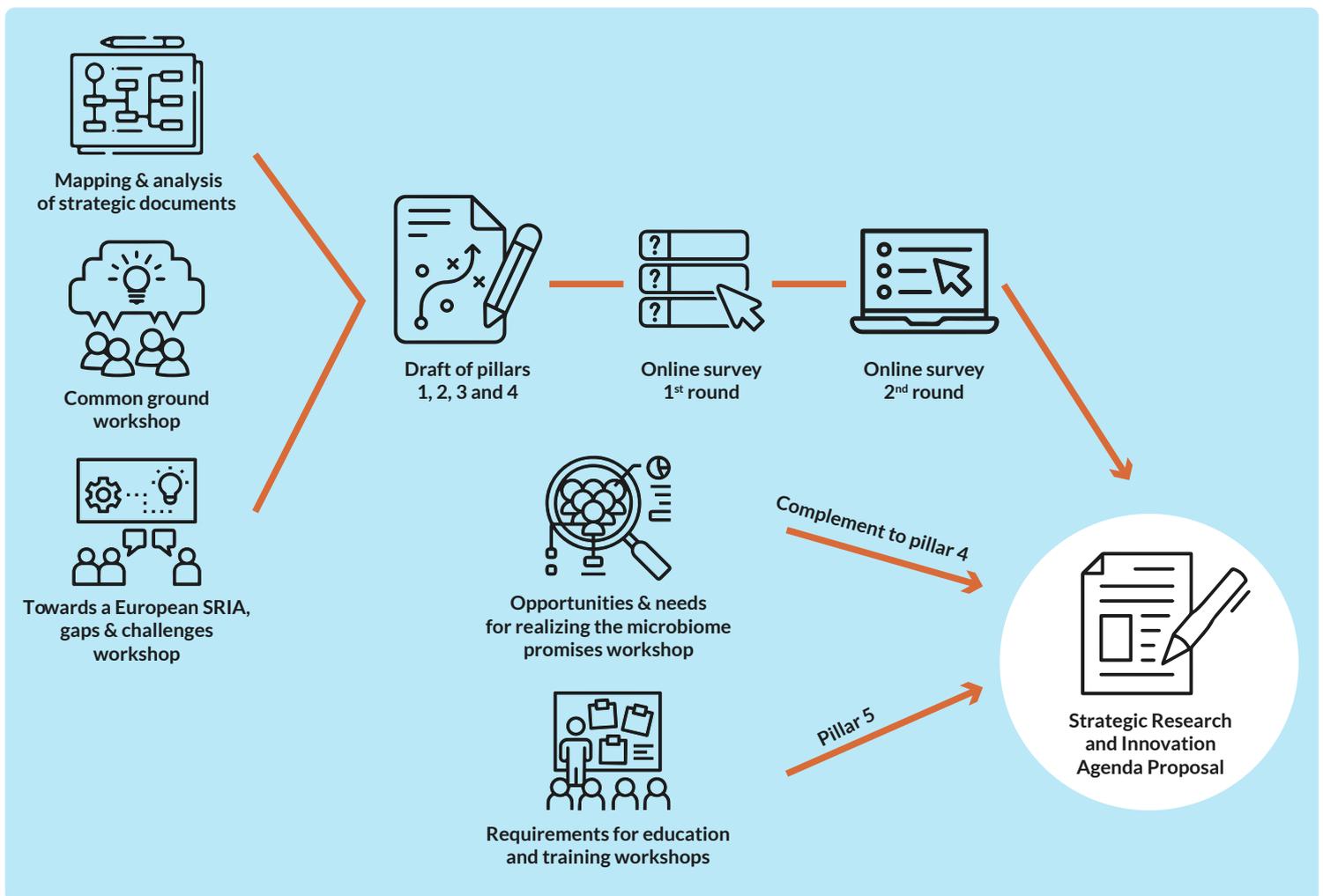
Considering the existing policy context, the *MS-CSA* project has endorsed the concept of the food systems approach for microbiome research. It encourages future initiatives to use a systems approach covering the whole chain of production and to work in an interdisciplinary and transdisciplinary way 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 MS-CSA 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.

The mapping performed in MicrobiomeSupport by WUR with other MS-CSA task contributors involved all the project partners in a global mapping process rounded off 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 connecting 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, and 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 also used to organise a workshop, entitled Towards 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 in the field, industry representatives, policy-makers, academics, R&I actors, etc. These consultations were carried out in March and December 2021 and a total of 200 replies were received from 33 countries. 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.

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

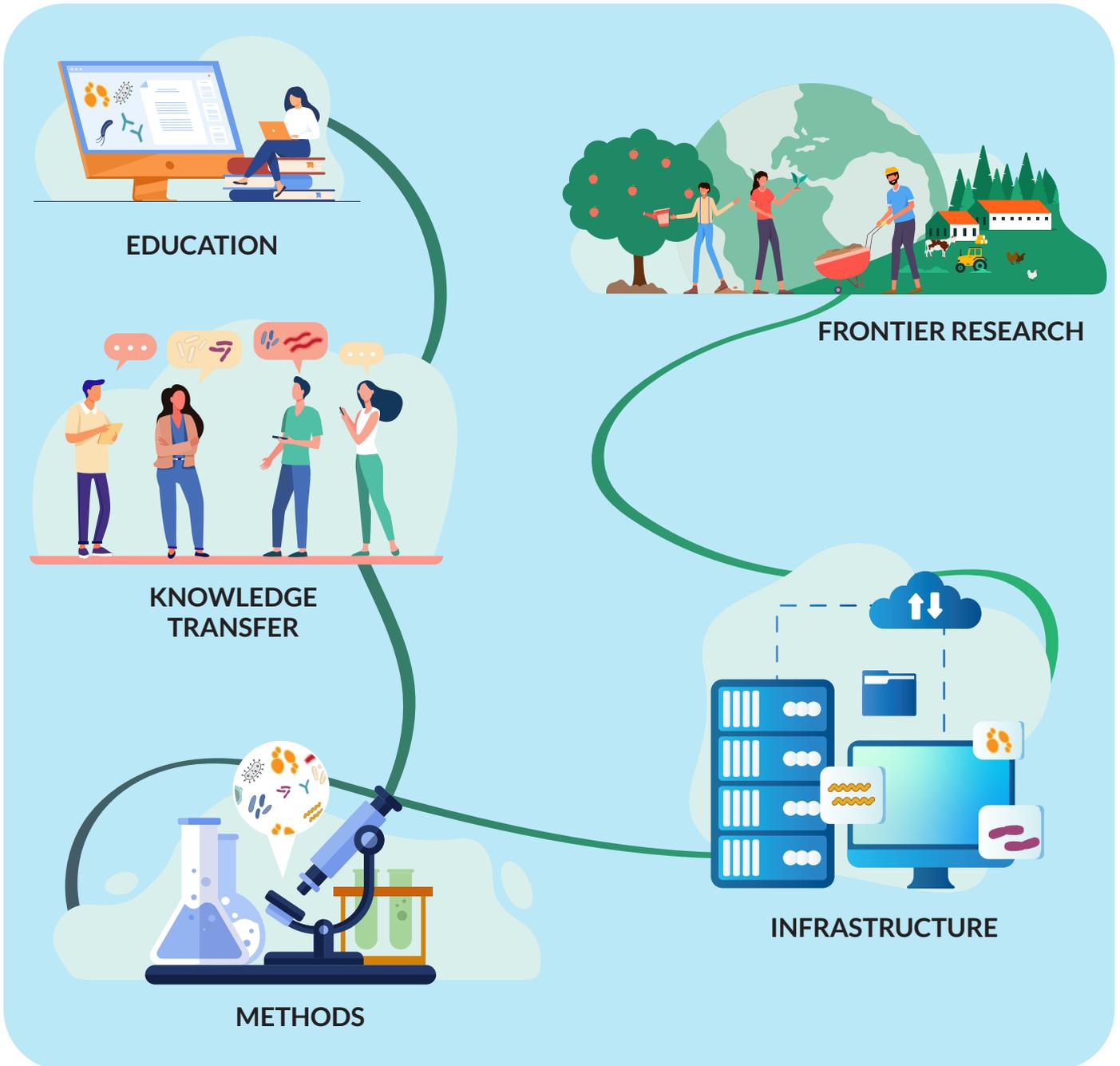
It is important, particularly for fast-growing scientific fields, to consider the regulatory frameworks that apply to emerging and future innovations that will need to be approved for their intended use. For this purpose, CSIC with other MS-CSA task contributors organised a trans-sectoral workshop entitled 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, etc.) and other multi-disciplinary aspects.

For this purpose, FFoQSI and other MS-CSA task contributors organised a workshop entitled Educational Needs (Nov. 2021) to bring 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) to work on clarifying microbiome-related educational needs in food systems. During the workshop, the educational needs in microbiome research for public health, academia, and industry were discussed.

4. The MicrobiomeSupport Strategic Research and Innovation Agenda

The SRIA is composed of five interconnected pillars:





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 key to maintaining its healthy functioning. Key parameters of the food system can be influenced by such communities. Soil health, plant productivity, and animal and human health are just a few examples where they have an impact. Maintaining host-associated microbial biodiversity holds potential direct economic benefits for many economic sectors. This biodiversity is crucial for safeguarding EU and global food security. Biodiversity is a key pillar of food security, nutrition, and diet quality. It is the ultimate source of food variety and underpins the ecosystem services that sustain life. It is an integral determinant of health and often a vital component in healthy and livelihood outcomes. Its loss would jeopardise food systems, putting food security and nutrition at risk. To foster advances in microbiome-related research for safer, healthier, and more environmentally-friendly food systems, ***we need a 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 insights into new solutions and the possibility of developing 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 would 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 featuring 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, the identification of 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, new antimicrobials, etc.

Changes in agri-food practices, as well as 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 into 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. probiotics) 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.

GOAL 2

Identify geographical/temporal changes (in connection with resource variation).



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

GOAL 1

Understand interactions between microbes 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 microbes.
- Systemic ecology approaches at the food system scale.



KEY TARGET: Harness unknown functional diversity. From the Horizon Europe Strategic Plan (2021–2024): R&I can improve conservation, management, and use of fungal and bacterial genetic resources, thereby preserving and enhancing biodiversity in natural and primary production systems.

GOAL 1

Comprehensively characterise functional diversity.

- Metabolic/proteomic profiles.



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 in order to set out strategies for mitigating this spread.

GOAL 2

Develop alternatives to current antimicrobials.

- Discover new, isolated 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 microbes or treat refractory infections

MICROBIOMES TO BOOST SUSTAINABLE PRIMARY FOOD AND FEED PRODUCTION

The food system area of primary production (plants and animals) has a significant impact on system sustainability. As the prime prerequisite for food and nutrition security, sustainable agricultural systems, for instance, could deliver a number of economic, environmental, and health benefits. For farmers, who are the backbone of food systems and the frontline managers of natural resources, improved knowledge and use of microbial products will enhance plant and animal health and well-being, prevent interspecies disease transmission throughout the food system, and reduce farmers' 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 field combined with precision agriculture have led to the development of new strategies aiming at reducing the environmental footprint of agriculture and improving public health. This has spurred the development of biological products such as biopesticides and biofertilisers towards a more sustainable agriculture given their low toxicity and ability to at least partially replace their synthetic counterparts, controlling the burden of antimicrobial resistance and the emergence of zoonotic diseases while maintaining productivity and competitiveness. Microbiomes as key players in this field could contribute to the transition to resilient climate- and environmentally-friendly agricultural systems that provide consumers with safe, healthy, and sustainable food. They may influence soil fertility and productivity, crop and animal production, and carbon sequestration, and are in turn affected by changes in the food system.

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 of all 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 play a role in the development of more adapted varieties, gaining insights into the structures, functions, and interactions of soil microbiome communities between these crops and soils is required. A deeper understanding of soil microbial ecosystems on a **global scale** would be a prerequisite for the development of **innovative microbiome and microbial products**, including **markers of expected functionalities/services** and associated diagnostic tests, as well as soil remediation or restoration solutions. With this in mind, one could simply suggest that 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, pests and diseases, and other stresses, maintaining soil diversity, and supporting carbon capture and storage, with exciting opportunities for climate change mitigation.

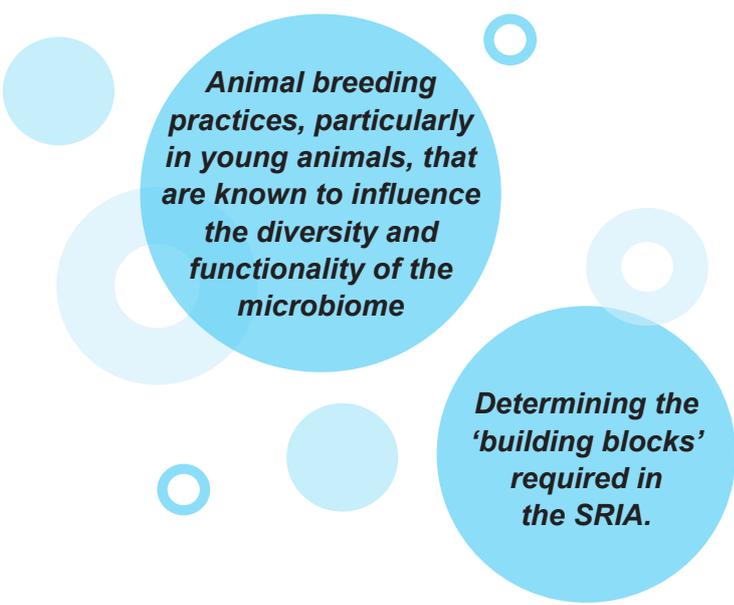
Mapping plant/crop-associated microbiomes at different **stages**, across diverse varieties, and in different geographic areas may help assess microbiome diversity and variability in association with plant yields and health in various environmental and climate conditions. Advanced research on the mechanisms of plant–microbe symbiosis and their effects on yield, nutrient acquisition, stress tolerance, and product quality for feed and food purposes would facilitate effective knowledge generation of and translation into reliable agricultural practices and data for farmers that would ultimately contribute to crop adaptation to climate change, synthetic pesticide reduction, and improved nutrient cycling. This would strengthen the expertise in Member States for the assessment of microbial product applications, such as biopesticides, biofertilisers, and biostimulants, all essential components of the transition to the European Green Deal.

Of equal importance is establishing causal inferences and gaining mechanistic insights into plant-microbe symbiosis and their effects on yield, nutrient acquisition, stress tolerance, food, and feed quality that could enhance plant health and productivity. This knowledge, coupled with an understanding of crop–microbe interactions, would help ensure the sustainability of a cropping system. Likewise, adopting science-based sustainable practices favouring the expression of microbiome functions and contributing 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 the expected potential application of microbiomes would need to be coupled with convenient agricultural practices (using biofertilisers, for instance, in line with the European Green Deal). Here, targeted studies are required to identify and validate microbes 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, the development of microbes/microbiome-enhanced food products, food supplements, and alternative food 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 also 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, through the production of cattle breeding lines, which shelter 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.



Animal breeding practices, particularly in young animals, that are known to influence the diversity and functionality of the microbiome

Determining the 'building blocks' required in the SRIA.

Since interventions on 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 could 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 would lead to a better understanding of antibiotic resistance and its spread in food systems and the environment.



KEY TARGET: Plant productivity and health.

GOAL 1

Explore individual microbes, 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 microbes 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: 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 soil microbes–other microbes interactions/microbiome–host interactions.

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: Animal production and health.

GOAL 1

Understand microbe–animal 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 at all stages of feed production and processing to reduce chemical inputs and residues.

GOAL 2

Exploit the microbiomes (microbes, functions, products) to optimise the use of co-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 up and down the food system, improving food safety, as well as offering protection against spoilage organisms. This will hopefully yield innovative food products at different scales, from home to industry, and meet consumers' expectations for transparency and environmentally-friendly foods in line with consumer demand for certified 'clean' foods. With the rise of a whole field of research around feed and food microbiomes and the rapid technological advances in various areas of the food system, significant insights have been provided into the landscape of food microbiomes and their potential as new biomarkers for food authentication and traceability.

In this regard, integration of such scattered knowledge and the creation of a reference database seem paramount to address the challenge of diversity and variability of feed and food microbial communities. This would enable new traceability systems across the food chain and leverage systematic authentication of the microbiome. 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 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 better preserve lifelong health and contribute to limiting 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. Still, the disruption of this symbiosis has been associated with a wide range of diseases and 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 microbiota-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 minimal standards and guidelines to reach a consensus on methods and references for assessing the effect of foods, food compounds, and diets on 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, more broadly, 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 based on microbial fermentation would also need further investigation as it currently accounts for 5% to 40% of dietary patterns in given populations [8]. The health benefits of fermented foods have in fact been acknowledged for centuries and stem from the presence of living microorganisms and the fermentation-associated modifications to the food product's ingredients. They could shape the composition of the gut microbiota and promote health-promoting metabolites linked to health benefits. More research should help develop sustainable dietary strategies based on microbial fermented foods, aiming at improving human health.

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 would also include the definition of strategies for the design of precision/personalised food products and diets. The latter need to be further developed to maintain 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 host–microbiota symbiosis, sustain healthy microbiomes at different life stages, and could have a significant potential for use in personalised nutrition.

Note that barriers and lock-ins in translating and implementing precision diets include a significant lack of standards, appropriate studies in this area, 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 TARGET: 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 treat non-communicable chronic diseases.

GOAL 3

Evaluate the effect of fermented foods on the human gut microbiome and on host parameters that are key to jointly support a healthy host–microbiota 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 waste and promoting resource recycling are both crucial in order to enhance food system sustainability. Microbiomes are omnipresent in the food system, making them drivers of sustainability and circularity.

Understanding the functions and mechanisms 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 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, for instance, 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 impact on food system microbiomes and the anticipation of necessary adaptation to these new conditions while still maintaining their performance and safety. Feed for livestock and aquaculture often compete for resources with food production. Upgrading or upcycling side-streams and by-products from food systems could alleviate this competition

and could 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 or some of their microorganisms 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, 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, 14]. 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 (to improve wastewater treatment, for instance, 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 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.

Transversal topics are cross-cutting priorities required for the development of knowledge and innovation. They have been designed on the basis of findings of the brainstorming sessions organised during the Common Ground Workshop. These findings were exploited to draw up the agenda and sessions for the trans-sectoral workshop entitled Microbiomes in food systems and the bioeconomy: toward a European research and innovation agenda co-organised by INRAE and AIT in March 2020.

The aim of this workshop was to identify and discuss needs and gaps in the current microbiome field of R&I and how to address them. The conclusions of this workshop, complemented by data from the literature, enabled us to identify cross-cutting issues in four main areas concerning research infrastructures, data access and sharing, knowledge transfer and innovation, and stakeholders and society awareness.



4.2. Capacity building for open microbiome research and innovation

INFRASTRUCTURE FOR PRESERVATION AND RESEARCH ON MICROBIOMES

To sustain and fuel research on complex microbiome systems, the development and establishment of suitable supporting infrastructure is a crucial success factor. 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 microbe-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/techniques 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. 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 (i.e. details on the origin of samples, date, health status, etc.) may overcome the lack of reusing samples and existing data [15]. Efforts and adequate preservation techniques must be coordinated to ensure functionality, build up knowledge, train researchers, and make the materials publicly available, including through the development of methods to replicate/multiply complex microbiomes. Appropriate incentives to make contents 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 that adequate infrastructure needs to be established. A selection of samples needs to be included and the challenge of the ownership of these samples solved.

In the context of research infrastructures, sharing of analytical capacities is key. Training for users at core analysis facilities should be provided 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 and harmonise methods and protocols.

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 and more 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 outside the country they are established in. 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 ensure comparative studies with data from other platforms and remaining repositories. International challenges (CAMI) that test the use of tools such as software providing minimal requirements are an interesting approach to reach 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 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 the access to and sharing of information through open source databases gathering information on food microbiomes. Various solutions such as a cloud-based repository might 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. Harmonisation of methods and standards

Consensus, accredited or certified reference materials, and standardised technologies such as global working standards 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 for protocols for data generation (metagenome, metatranscriptome, etc.) 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 need to be undertaken. New emerging methods, potential risks, and knowledge on a global level should be considered. The necessary infrastructure, technologies, and analysis tools should be affordable and accessible. Training avenues for researchers 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 could 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. 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 microbiome standardisation networks to speed up the harmonisation and co-evolution of technological development and standardisation.



4.4. Knowledge transfer and co-creation

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 consumer intake 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, produce proof of concepts, and shape new spaces for industry and 'self-made' products. Both systems-oriented analyses and more specific detailed analyses are needed to overcome knowledge gaps in the value chain; projects should be planned for a long time horizon and given suitable funding.

Harmonised legal frameworks and regulations, international alignment, and the establishment of network structures and platforms that address societal issues must move forward in step 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 their application opportunities needs 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 need to 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 that focus 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 science should advance in step with regulation. 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 as well as to increase the sustainability, productivity, safety, and nutritional quality of foods.
- There is a need to harmonise best practices and standards for microbiome analysis, including from sample collection, storage, and processing to in-silico bioinformatics analysis and 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 microbial communities per se, as well as 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), the Codex Alimentarius, etc.
- Regulatory assessments need to 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 each individual strain will not reflect the properties of the whole consortia but the status of the consortia; how to assess its overall function remains unclear.
- 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.
- Bridge the gap between scientists and regulators by developing a regulatory science curriculum at universities to train research actors in regulatory aspects and regulators in biological sciences.
- Develop a new type of R&I projects involving regulatory science experts in the project from conception and in pre-competitive projects.
- Develop an appropriate policy vision and implement measures that enable the use of the microbiome innovation potential.



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

GOAL 1

Set up international collaboration to identify best practices and standards for microbiome analysis and interpretation of the results.

GOAL 2

Identify 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.

MicrobiomeSupport has brought together experts from different microbiome domains and contributed through joint work to create a defragmented expert body on food systems microbiomes. This type of 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.



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.



4.5. 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 scientifically-supported microbiome applications by involving citizens and stakeholders throughout the whole supply chain (from primary production to end consumers) in certain R&I actions. Early, clear, easy-to-understand, and effective communication aimed at the general public is required. Stakeholder dialogues, creative living labs, national platforms, training of authorities, and inclusion of microbiomes in early education can be tools to raise awareness and establish tailor-made formats.

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. 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 so as 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 to getting food systems on track 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 (iii) 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 today is to instil knowledge about the microbiome from childhood. Supporting initiatives such as the International Microbiology Literacy Initiative (IMLI) that aim to provide new materials for teaching microbiology in schools to create a society that is proficient in key aspects of microbiology are important for everyday knowledge-based family decisions, as well as for 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 would the industry like to see happen? => To target common research projects to answer some of their questions and then make the effort of integrating curriculum design into these projects to make it applicable for professionals on the ground. Introduce training curriculum design at the EU level. Introduce non-academic training at the EU level. Support is needed for the development of large European-wide training programmes.

5. Requirements for implementation

This SRIA highlights a number of challenges and priorities that need to be addressed in order to meet expectations and transform our food systems toward sustainable development. MicrobiomeSupport has brought together experts of different microbiome environments and contributed through joint work to create a defragmented expert body on food systems microbiomes, from soil to consumers and considering upcycling of by-products and bioremediation processes in a 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 activities/stakeholders to maximise research impact and sustainability favouring harmonised practices in line with technological developments;***
- Enhance sharing and capitalisation of activities, results, and innovations of past, current, and future projects.***

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