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Microbiome innovations for a sustainable future

The United Nations Sustainable Development Goals (SDGs) are being integrated into bioeconomy strategies around the world, including the European Green Deal. We highlight how microbiome-based innovations can contribute to policies that interface with the SDGs and argue that international cooperation in microbiome science is crucial for success.

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In 2015, the United Nations General Assembly adopted 17 Sustainable Development Goals (SDGs) that aim to improve the lives of people around the world. A 15-year programme for global sustainable development was set out, with the SDGs forming the backbone of this plan. Many nations incorporated the SDGs into government policies by adopting national bioeconomy strategies to achieve the SDGs and setting targets to mitigate climate change.

Bioeconomy strategies embrace sustainability and circularity principles such as the production of food, materials and energy from renewable biological resources including crops, forests, fish, animals and microorganisms[1]. Such strategies aim to ensure a sustainable increase of primary production and enable economies to rely less on fossil-based fuels and other non-sustainable resources, and more on renewable and reusable resources, including waste. Bioeconomy strategies have converged with the aims of the SDGs as bioeconomy solutions are key to sustainable production that protects natural resources and biodiversity, and follows circular concepts.

In response to the SDGs and the 2015 United Nations Climate Change Conference (COP 21), the European Union (EU) implemented the Bioeconomy Strategy[1] and, more recently, the ambitious EU Green Deal. The latter aims to reduce net emissions of greenhouse gases (GHGs) to zero by 2050, while ensuring the prosperity of the European economy and the well-being of its citizens. An important policy supporting these strategies is the Food 2030 agenda that was launched in 2016 (ref. [2]). This policy provides a framework for transforming food systems into resilient systems to ensure that everyone has access to affordable and healthy food. Food systems need to deliver co-benefits for people's health, our

Box 1 | Examples of bioeconomy and climate-mitigating strategies in IBF countries

New Zealand, like the EU, has set the target to realize a net-zero emission of GHGs by 2050 (ref. [14]). An exception is made for methane owing to the dominant role of livestock in New Zealand and an international lack of options to reduce emissions; this 2050 target is therefore a reduction of 24–47% compared to 2017 levels. Understanding the plant and rumen microbiome has resulted in the isolation of low-GHG-producing feeds and of traits in sheep that reduce methane emissions, and continued progress for a vaccine that is currently able to reduce methane emissions from 2017 levels by 20%.

The Pan-Canadian Framework on Clean Growth and Climate Change was published in 2016 in response to the Paris Agreement. The Canadian Climate Change Policy has goals that integrate soil and water conservation, carbon sequestration in soil, and reduction of GHG emissions in livestock and crop operations (http://go.nature.com/3hOmrG4). Microbiome research is embraced to tackle the respiratory and intestinal tract in livestock animals and to reduce antimicrobial use. Together with soil and plant microbiome knowledge, an ecosystem approach is being developed to reduce GHG emissions and chemical and nutrient runoff.

Australia has several policies, implying different agencies and Cooperative Research Centres (for food waste, food agility, soil and the blue economy, for example) that are contributing to realizing a bioeconomy and ambitious climate targets[15]. By 2030, Australia will reduce emissions to 26–28% compared to 2005 levels — a target representing a 50–52% reduction in emissions per capita and a 64–65% reduction in the emissions intensity of the economy between 2005 and 2030.

The United States' bioeconomy policy acknowledges the importance and values of the bioeconomy for sustainable economic growth and job creation, and its contribution to human health, food, nutrition, energy and the environment, and mostly focusses on the economic added value, not referring to SDGs or climate goals. Although the country withdrew from the Paris Agreement in 2017, the bioeconomy strategy will contribute to the shift towards renewable resources. In addition, 25 states joined the United States Climate Alliance to reduce GHG emissions in accordance with the Paris Agreement. The United States uses a variety of baseline years, ranging from 1990 to 2006, and uses different years for the ultimate target, although most states have 2050 as the ultimate target year to reduce GHG emissions.

The Republic of South Africa aims to address its socio-economic development goals of poverty reduction to improve the quality of life with its bioeconomy strategy. The strategy supports the country's efforts to shift towards a low carbon economy while enhancing food security and creating a greener economy. Bioeconomy also represents a strategic option for Argentina, who signed an agreement with the Inter-American Institute for Cooperation on Agriculture in 2018 to become the continent hub for bioeconomy, and contributed to the Economic Commission for Latin America and the Caribbean concept note *Towards a Sustainable Bioeconomy in Latin America and the Caribbean: Elements for a Regional Vision*. The Ministry of Agroindustry considers the bioeconomy as an important opportunity to generate economic progress and access world markets, as well as to respond to its climate change commitments.

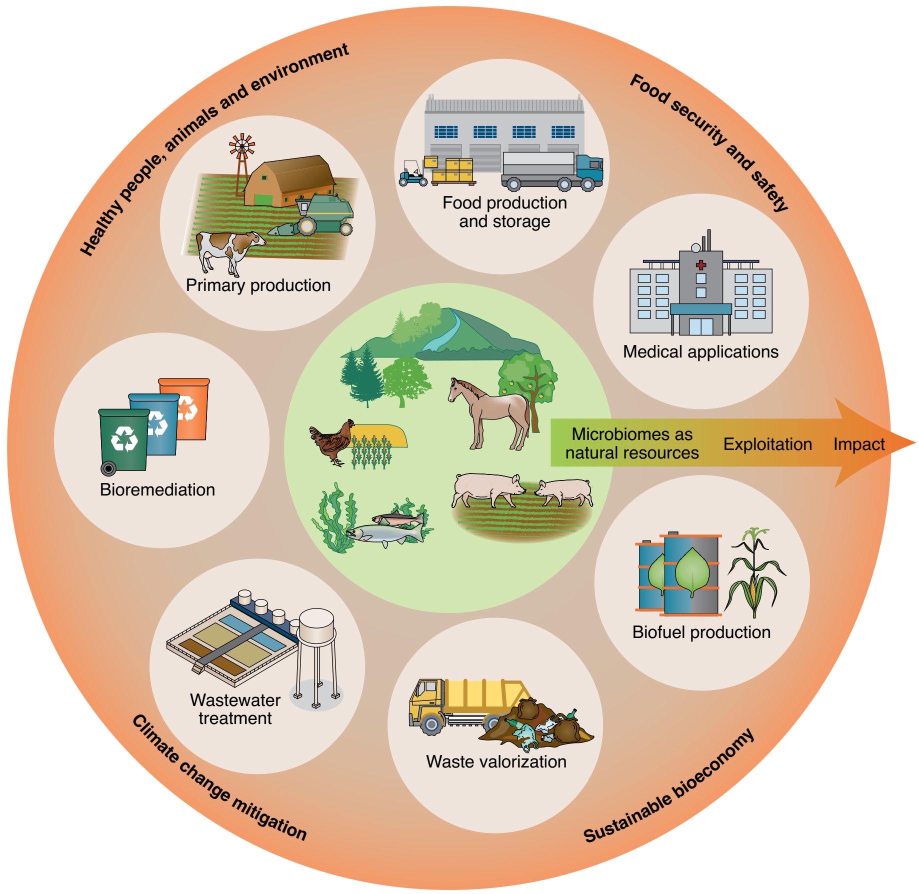

Fig. 1 | Microbiome services. Microbiomes are natural resources that exist across ecosystems. They can be exploited for various services with a beneficial impact on pressing societal matters.

climate, planet and communities within safe planetary boundaries.

Similar strategies and policies have been adopted in other non-European countries. The International Bioeconomy Forum (IBF; https://www.bioeconomy-forum.org/) was formed in 2017 to enable international cooperation on shared science research and policies for the development of a successful global bioeconomy. The IBF members include the EU, Canada, United States, Argentina, South Africa, India, New Zealand and China. An overview of the respective strategies of selected IBF members is provided in Box 1.

Policies to promote sustainable bioeconomy are high on the agenda of the IBF. One of four IBF working groups is focusing on applications of microbiome technologies in the food system and how these might be scaled up through international collaborations to provide more effective long-term impact and to promote sustainable bioeconomy globally. Microbiomes were identified as being of horizontal importance to realize a true and circular bioeconomy.

A microbiome is a microbial community — comprising viruses, bacteria, archaea, unicellular eukaryotes and fungi — that is characteristic of a specific habitat[3]. Microbiomes have crucial roles in maintaining life on Earth. For example, marine microbiomes produce most of the oxygen that we breathe and have indispensable roles in carbon sequestration and nutrient cycling. Soil microbiomes fix nitrogen (N_2) and methane (CH_4), enabling fertilization and GHG mitigation effects. The human gut microbiome has clear links with human health; similarly, plant and animal microbiomes have important roles in plant and animal health.

Our growing understanding of the interconnectedness of microbiomes in environmental and food systems (Figs. 1 and 2) suggests that microbiome innovations have the potential to improve sustainable food, feed and biofuel production whilst underpinning the principles of circularity. For example, applications of natural or engineered microbiomes to degrade organic and waste materials into nutrients in food and fibre chains might enable a more sustainable fuel industry[4]. Progress is also being made in the application of plant microbiomes for increasing crop yields and improving salt and drought tolerance of crops[5]. Soil microbiomes can be applied as bio-fertilizers for soils and can reduce nitrogen leaching[6]. The role of food microbiomes in the production and preservation of fermented foods such as bread, chocolate, beer, yoghurt, kefir and kimchee is undergoing a renaissance owing to the application of genomics technologies to understand the composition and functions of food microbiomes[7]. The use of environmental microbiomes for the bioremediation and degradation of toxic contaminants and waste products is expected to accelerate the development of a circular bioeconomy[8].

In our role as an international consortium comprising microbiome scientists and policy-makers, we argue that microbiome applications could underpin solutions to tackle global challenges such as food safety, food and nutrition security, health and well-being, waste management and climate change adaptation and mitigation. Such applications would contribute substantially to realizing the goals of global bioeconomy strategies and achieving the SDGs. Table 1 gives an overview of areas in which microbiome innovation could help to achieve the SDGs.

The potential of microbiome applications to support the development of a mature bioeconomy and the achievement of the climate mitigation goals has been acknowledged by numerous organizations. In its recent report, the World Economic Forum (https://www.weforum.org/) described how microbiome technologies could increase primary production by up to 250 million tons while simultaneously reducing GHG emissions by up to 30 megatons of CO_2 equivalents, mainly through reducing the use of inorganic fertilizers. Microbiome technologies together with genomics, gene editing and synthetic biology were identified as being key to accelerating bio-innovation in food systems: they are one of 12 promising technologies that could transform food systems in the next decade, while fully adopting the SDGs. The Food and Agriculture Organization of the United Nations (FAO) also recognized the potential of microbiomes for enhancement of health, climate and sustainable food systems[9]. The FAO has highlighted a crucial role for soil microbiomes in food production, food safety and environmental sustainability. The FAO further pointed to the use of aquatic microbiome applications to ensure the supply of alternative protein sources for

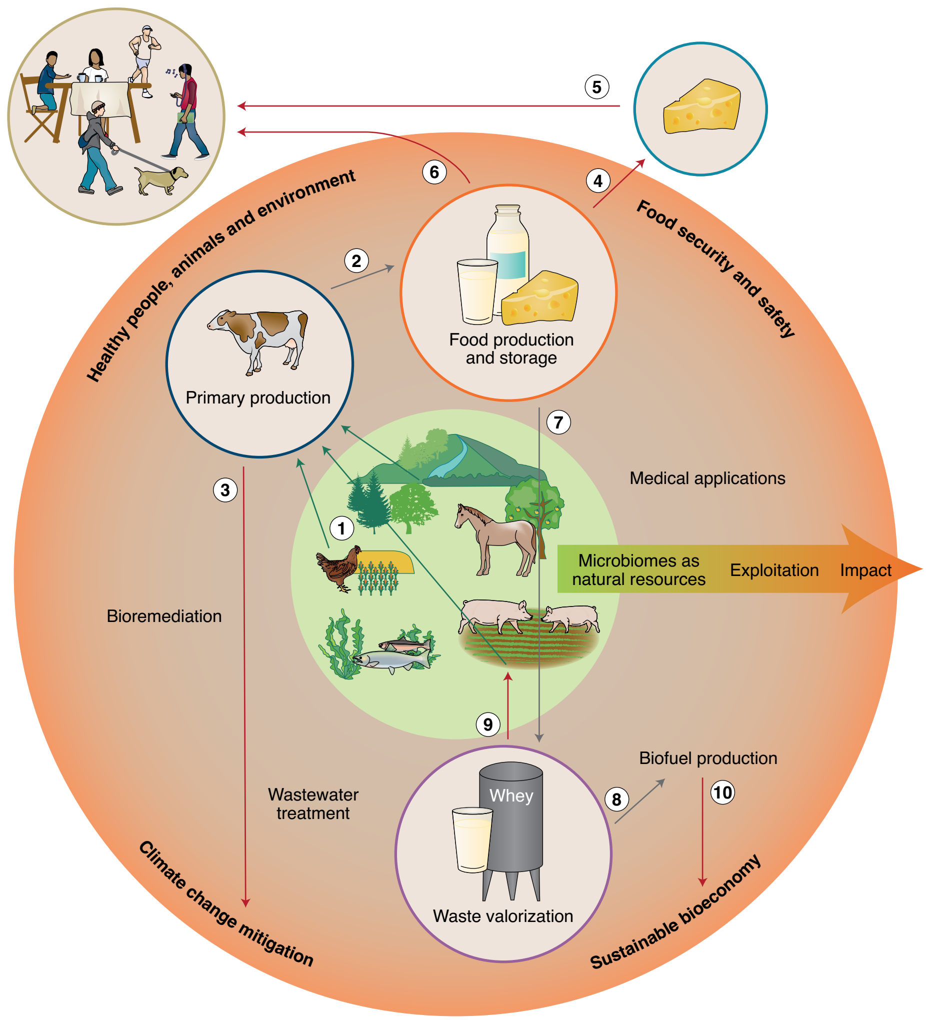

Fig. 2 | Microbiome connectivity and impact pathways using dairy as example. Feed impacts on the animal microbiome (1), which affects raw milk and product quality (2) and climate (3). The microbiome of food products impacts on food safety (4) and on human health directly and indirectly through interactions with the gut microbiome (5,6). Production waste (7) such as whey can be utilized for biofuel production (8) and in animal feed (9) to support a sustainable bioeconomy (10). Green arrows show microbiome exploitation opportunities; grey arrows show links between exploitation chains; and red arrows show the impact on societal challenges and policy goals.

food through aquaculture[10]. Probiotics that improve fish health or microbial products that improve water quality are two ways this might be achieved[10]. FAO collaborates with scientists and policy-makers to promote microbiome management as a part of policy decisions. 'The microbiome world' has also been identified as one of ten pathways to action that will be implemented under Horizon Europe to find solutions to the priorities of Food 2030.

Before any of the goals we outline can be achieved, we need more research. Despite the promise of microbiome applications, the rush to develop them should be tempered by the need to fully understand the systems in which they function. Although research on microbiomes continues apace, few biochemical pathways or interactions in food systems are well characterized (Fig. 2). A multidisciplinary approach is required to enable safe and reliable microbiome innovations. Research efforts need to advance microbiome-related knowledge from description to functional understanding and should address the potential impacts of one part of the food chain (such as primary production) on another (such as human/gut health). This will require collaboration between researchers in the fields of genetics, microbiology, ecology, soil health, animal health, plant health and human health, and should be supported by access to infrastructures enabling data management, standardization and bioinformatics, as well as biobanking of microbiomes. The sharing of data will be crucial.

The areas of microbiome-related expertise are being brought together in new microbiome centres[11]. Long-term investment is needed to ensure the value chain is understood and that applications are brought to market. International cooperation involving multiple partners and stakeholders from different continents and living conditions is crucial for understanding microbiomes in the context of finding solutions for global challenges. Robust international cooperation will require the alignment of global research agendas and funding to enable fair and equitable global partnerships and knowledge sharing. Towards this, the European project MicrobiomeSupport (www.microbiomesupport.eu), in collaboration with a variety of global stakeholders, have designed a shared strategic research and innovation agenda for food systems microbiomes that opened for consultations in autumn 2020. Further alignment and coordination can be accomplished through the IBF.

Another requirement is to build public trust in microbiome innovations. To achieve this, there is a need to create public awareness through education. Communication between researchers, innovators, policy-makers, regulatory bodies, industry actors, technology users (including farmers) and the general public is needed to ensure that innovations are commercialized and adopted. Developing ethics and regulatory guidelines on how new microbiome applications could be introduced responsibly into production systems will increase the likelihood of public acceptance.

Food systems are global, so scientists and innovators need clear information about the legal requirements aimed at the fair and equitable sharing of benefits arising from the use of natural genetic resources of microbiomes. In this regard, there is a need for transparency in the national laws of provider countries and clarity at the international level. A good example is the Convention on Biological Diversity, which was established to protect biodiversity, ensure a sustainable use (of components) of biological diversity and realize an equitable sharing of benefits from using these resources. New or adapted regulations on developing, registering and introducing microbiome products consisting of complex consortia are needed.

The huge potential of microbiomes to improve and support food systems and

Table 1 | How microbiome technologies could contribute to SDGs

Area	Microbiome roles	SDGs[a]	Green Deal
Food supply in industrialized and urbanized societies	Microbiome-based plant protection and nutrition products consisting of single or multiple microorganisms for improved nutrient cycles, low input agriculture and yield stability. For example, *Bacillus*- or *Trichoderma*-based biopesticides, and bio-fertilizers with arbuscular mycorrhiza fungi or phosphate-solubilizing bacteria. Microbiome-based solutions (probiotics and microbiome engineering) for animal health and productivity. Probiotics containing a mixture of several species or strains of *Bifidobacterium, Candida, Enterococcus, Lactobacillus, Pediococcus* and *Streptococcus*. Integration of microbiomes in smart farming practices (including indoor and urban farming) for better stress resilience and pest and weed management. This may include microorganisms applied as bio-fertilizers, biocontrol agents and bio-herbicides, and improved microbiome understanding pinpointing (for example, via prediction models) to management practices that ensure the maintenance of soil health. Microbiome-based approaches to improve food safety and reduce antimicrobial resistance, and to enhance the nutritional quality of food and reduce post-harvest food losses. For example, microorganisms can be applied to reduce human pathogen loads or increase the nutritional value of plants.	SDG1, SDG2, SDG8, SDG11, SDG12	Resource efficiency. No net emissions of GHGs. From Farm to Fork: a fair, healthy and environmentally friendly food system. Reduce use of antibiotics, chemical pesticides and fertilizers.
Climate change mitigation	Integration of microbiomes in smart farming practices (including animal/fish production and urban farming) for reduced GHG emissions. Integration of microbiomes in the circular bioeconomy for improved recycling, exploring the full potential of (biogeochemical) cycles, the valorization of waste/co-products and new energy concepts. For example, microbiomes or microbiome-derived enzymes may be implemented in waste valorization. Making use of microbial pathways for environmental remediation. Knowledge-based usage of natural resources (such as soil) for reduced GHG emissions and impacts on biodiversity (for example, by cropping a specific crop and optimizing (bio)fertilizer addition).	SDG7, SDG8, SDG13	No net emissions of GHGs. Resource efficiency. Preserving and restoring ecosystems and biodiversity. A new circular economy action plan, including a sustainable products policy. Transition resource-intensive sectors, such as textiles, construction, electronics and plastics. Carbon capture.
Healthy lives	Integration of microbiomes in a One Health approach to improve human health from farm to fork to gut with a healthy diet and fewer chemical inputs, enhanced nutritional quality and better management of antimicrobial resistance. Following a food systems approach and understanding the connection of microbiomes in different environments along the food chain, as well as the impact of environmental disturbance on microbiomes and horizontal gene transfer, will combat the spread of antimicrobial resistance genes. Microbiome-encoded new antimicrobials and therapeutics. Microbiomes host a wealth of new bioactive substances serving as potential therapeutics for the future.	SDG3	A toxic-free environment to protect citizens and the environment better against hazardous chemicals, and encourage innovation for the development of safe and sustainable alternatives. Zero pollution/toxic-free environment. Reduced use of antibiotics, pesticides and fertilizers.
Clean environment	Integration of microbiomes in technologies for environmental remediation and restoration. For example, those combining conventional (physical, mechanical) and microbial restoration approaches making use of degradation activities of microbiomes. Making use of microbiomes in farming practices (crop production, forestry, animal production and aquaculture) to protect biodiversity and ecosystem functions. Integration of microbiomes in a circular bioeconomy valorizing waste material. Using microbiome functions for the generation of new biodegradable and environmentally safe materials (for example, microbial bio-based polymers such as exopolysaccharides), which can be further used to generate new materials. Using microbiomes as indicators for monitoring and early intervention. Protecting microbial biodiversity as a source of microbiome-encoded, novel compounds. Consideration of microbiomes in the built environment for improving indoor environmental quality (for example, air) by using appropriate building materials or integrating appropriate plants in building concepts promoting microbiomes which benefit human health and well-being.	SDG6, SDG8, SDG14, SDG15	Plastic challenge. Waste reduction. Biodiversity. Preserving Europe's natural capital. Forest ecosystems. Sustainable blue economy. Zero pollution/toxic-free environment.

[a] SDG1: end poverty in all its forms everywhere; SDG2: end hunger, achieve food security and improved nutrition and promote sustainable agriculture; SDG3: ensure healthy lives and promote well-being for all at all ages; SDG6: ensure availability and sustainable management of water and sanitation for all; SDG7: ensure access to affordable, reliable, sustainable and modern energy for all; SDG8: promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all; SDG11: make cities and human settlements inclusive, safe, resilient and sustainable; SDG12: ensure sustainable consumption and production patterns; SDG13: take urgent action to combat climate change and its impacts; SDG14: conserve and sustainably use the oceans, seas and marine resources for sustainable development; SDG15: protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

the bioeconomy is just beginning to be understood and microbiome innovations have only recently started to reach the market[12]. Microbiomes may provide a wealth of bioactive compounds and activities that are beneficial for agriculture, environment and animal and human health[13]. Seizing the opportunities of microbiome innovations through investment, collaboration, regulatory changes and public outreach will greatly increase the likelihood of achieving the SDGs. ❐

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Competing interests

The authors declare no competing interests.