Where are microbiomes, and why are they important?

Applications and challenges in human, animal and environmental microbiomes

What is a microbiome?

Microbes do not exist in isolation [1]. Instead, they live in complex and dynamic communities in which different microbial species are constantly interacting [1]. When these communities are combined with a specific host (for example, humans, animals and plants) or environment (for example, soil and oceans), we refer to the ecosystem as a microbiome [1].

Microbiomes contribute to fundamental life processes, from influencing nutrient absorption and immune system development in the human gut to supporting plant growth and nutrient cycling in soil [2]. As complex systems, microbiomes can be affected by small changes in our ecosystems, for example, through the food we eat and the medicines we consume, such as antibiotics [3].

Microbiome research has far-reaching applications across human, animal and environmental health, from strengthening global food security to combatting disease and improving animal welfare.

The health of humans, animals and the environment are closely linked and interdependent [4]. Microbiomes serve as a critical link between humans, animals and the environment and are a key contributor to the health of ecosystems [5].

The environmental microbiome

Micro-organisms thrive in nearly every environment on Earth, from deep ocean sediments to high mountain peaks, the upper atmosphere, and even space [6,7]. Even man-made environments such as buildings and vehicles host microbiomes that influence disease transmission and ultimately human health [8].

Microbiomes in the soil, oceans and air play vital roles in a wide range of ecosystem processes essential to life on Earth, including the cycling of key nutrients such as carbon and nitrogen [8]. While the full diversity and function of environmental microbiomes are vast, this briefing focuses on the soil microbiome [5].

This diverse cast of micro-organisms perform many different functions, which are specific to their species and linked to various effects on environmental, human and animal well-being [6].

What is the soil microbiome?

Soil is teeming with micro-organisms, harbouring the most diverse and complex microbiome on Earth [5,9]. One gram of healthy soil is typically home to millions of micro-organisms belonging to over 50,000 different species [5,10].

The soil microbiome plays a crucial and multifaceted role in supporting plant health and ecosystem function [10]. Soil microbiomes decompose organic matter and recycle nutrients, supporting soil fertility, water retention and plant growth [2]. They deliver plants with 14 of the 17 essential elements fundamental to their health, including nitrogen and phosphorus [5,11]. Soil microbiomes also contribute to climate change mitigation by removing carbon dioxide from the atmosphere, primarily via photosynthesis, and storing carbon in the soil [6,12]. Other important contributions of the soil microbiome include:

- Conferring disease resistance to plants in disease-suppressive soils, where microbiome composition and activities compete with pathogenic (disease-causing) micro-organisms and stimulate the plant immune response [5,10].
- Promoting stress tolerance in plants, increasing their resilience to environmental changes such as fluctuations in temperature and moisture [5].
- Degrading and transforming toxic compounds (for example, antibiotics, pesticides and heavy metals), which impact plant productivity, water quality and ecological functions [6].

The soil microbiome influences the health of humans and animals by impacting the growth and nutritional quality of the plants they consume [5,6]. By supporting the health of animals, the soil microbiome also contributes to carnivorous animal and human health through the food chain [5]. Ultimately, soil microbiomes strengthen global food security [6].

What are the main challenges facing the soil microbiome?

Despite the critical importance of the soil microbiome, intensive agricultural practices often overlook and diminish beneficial microbial diversity and function [10]. These practices can also foster harmful microbial activity, such as the spread of antimicrobial resistance (AMR), ultimately reducing crop yields, increasing costs and exacerbating environmental damage [10]. For example, the widespread use of azole fungicides (azoles) in agriculture can drive resistance in *Aspergillus* species to these critical antifungal treatments [13]. This is particularly concerning for *Aspergillus fumigatus*, a pathogen of plants, animals and humans that relies heavily on azoles for treatment [14].

Antibiotics, microplastics and pesticides are among the chemical pollutants that can disrupt the soil microbiome [5]. Soil is frequently contaminated by hospital waste, manure and effluents from wastewater treatment and aquaculture, thereby acting as a reservoir for AMR [5,15].

Resistant micro-organisms can persist in soil and be transferred to vegetables, ultimately being ingested by humans and animals [5].

How can soil microbiomes be used?

Sustainable agricultural practices can harness the soil microbiome to improve soil health, crop yield, environmental sustainability and ecosystem resilience [2]. Soil management methods such as crop rotation (alternating different crops in the same field over time) and intercropping (growing different crops together in the same field) can enhance the diversity and function of beneficial microbiomes associated with different crops [10].

Introducing or promoting beneficial micro-organisms can also enhance soil health [8]. For example, mycorrhizal fungi form symbiotic relationships with plants at their roots, increasing water and nutrient uptake [5]. In agriculture, farmers can use these fungi as biofertilisers to increase crop growth by up to 50% and significantly promote crop yield [5].

Research into the soil microbiome could lead to the discovery of micro-organisms that can be used as biofertilisers and biopesticides, or that produce antimicrobial compounds [10,16]. The use of microbial-derived biofertilisers and biopesticides reduces dependency on environmentally damaging agrochemicals, such as chemical fertilisers, fungicides and pesticides [2].

Using nitrogen-fixing bacteria to boost sustainable crop productivity

In Brazil, nitrogen-fixing bacteria sourced from plant root microbiomes and applied to soybean crops have revolutionised farming, according to data from 2012 to 2020 [17]. It is estimated that nitrogen-fixing bacteria have reduced Brazilian fertiliser costs by US $10 billion, while cutting annual greenhouse gas emissions by 430 million tonnes [17].

The development was supported by the UK-Brazil Nitrogen Fixation Centre, with contributions from the University of Oxford, the John Innes Centre and Aberystwyth University [17,18]. This expertise could be leveraged to tackle food security challenges in the UK.

The human microbiome

Where are microbiomes found in humans?

Microbiomes exist almost everywhere in the human body and are intimately linked to our evolution, metabolic function, health and disease [2,19]. The microbiomes that inhabit our various body sites — such as the gut, skin, mouth and vagina — are uniquely adapted to the specific conditions and selective pressures of their respective environments [19].

The gut microbiome

The human large intestine is host to the most densely populated microbiome in the body, which influences digestion, nutrient absorption, metabolism and immune function [2]. Much of our knowledge on the human microbiome comes from studying the microbiome associated with this part of the gut. Our gut microbiome plays a fundamental role in our health from an early age [6]. The infant gut microbiome first develops after encountering micro-organisms in the birth canal [20]. Consequently, babies delivered by C-section host a different gut microbiome and may be more likely to develop allergies and autoimmune disease in later life [20,21]. Find out more in our briefing about the human gut microbiome **here**.

The oral microbiome

The oral microbiome, which inhabits the hard and soft tissues of our mouths, is fundamental for maintaining oral health [19].

Imbalances in the oral microbiome can lead to the build-up of dental biofilms on tooth surfaces, which can lead to tooth decay (cavities) and gum disease [19]. The composition of the oral microbiome even influences health conditions beyond the mouth, such as cardiovascular conditions, diabetes and respiratory infections [19]. Simple daily habits, such as brushing teeth twice daily, flossing and using mouthwash, can support a beneficial oral microbiome [19].

The skin microbiome

The skin microbiome is essential for maintaining our skin health and barrier function, for example, playing a central role in skin defence, protecting against pathogenic infections and modulating immune responses such as inflammation [19]. The composition of the skin microbiome varies significantly across different body sites, as microbial communities adapt to the unique conditions of each area, such as moisture levels, pH and environmental exposure [19]. Imbalances in skin microbiomes are associated with conditions such as acne, eczema and psoriasis [19].

The vaginal microbiome

The vaginal microbiome plays a vital role in women's reproductive and overall health [22,23]. A beneficial vaginal microbiome is dominated by *Lactobacillus* species, which produce antimicrobial compounds that help protect against infections, such as bacterial vaginosis, and create a favourable environment for sperm [22,23].

How can microbiomes in humans be harnessed?

Public attention is firmly on the potential of microbiomes, with the global human microbiome market projected to reach US $1.2 billion by 2030 [1].

Modulating human microbiomes for health benefits

Prebiotics and probiotics can be used to modulate and restore balance to the human microbiome, conferring health benefits and helping to manage microbiome-linked health conditions [19,24]. Prebiotics are substrates that are selectively utilised by host micro-organisms, whereas probiotics are live micro-organisms and should be consumed in adequate amounts [19,24].

Prebiotics and probiotics can be ingested or applied directly to different areas of the body (for example, mouth, skin and vagina) [19,25].

The prebiotic inulin

Inulin is a prebiotic fibre found in foods like bananas, garlic, onions and chicory [26]. It is also available as a concentrated prebiotic supplement, typically extracted from chicory roots, and ingested to promote normal digestion [27]. Inulin works by stimulating bacterial growth in the gut, increasing stool frequency and increasing faecal bulk [28].

Inulin is the only prebiotic with an approved health claim by the European Food Safety Authority (EFSA) [20]. Companies can advertise that consuming inulin "contributes to the maintenance of normal defecation by increasing stool frequency" [27].

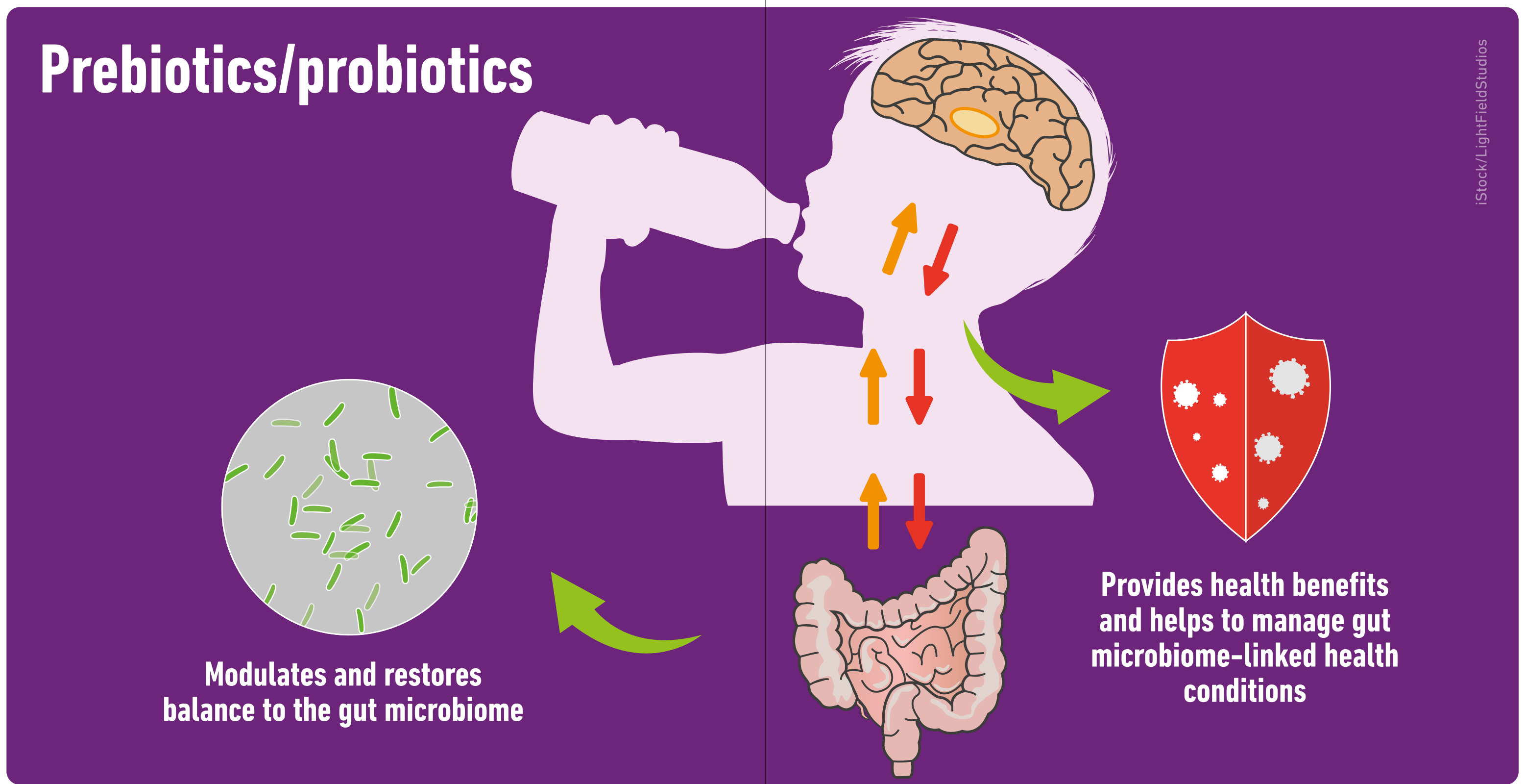
Using changes in microbiomes for disease diagnosis

Imbalances in the gut and oral microbiome are associated with cancer, as well as inflammatory, neurological and metabolic diseases [2,19,29]. The human microbiome and its metabolites therefore have the potential to serve as diagnostic biomarkers for early disease detection [29].

What are the main challenges in human microbiome applications?

While the safety and efficacy of some probiotics are well-established, their effects are specific to the strain used and condition treated [6,19]. There are potential risks of probiotic use in immunocompromised patients and neonatal intensive care settings, highlighting the importance of rigorous safety assessment and risk management strategies in product development and clinical applications [19]. The regulation of prebiotics and probiotics can present significant barriers to translating microbiome research into real-world applications [8]. One challenge is the uncertainty around how these products should be classified and regulated [8]. While they are typically marketed as food products or dietary supplements, they can also fall under other regulatory categories such as cosmetics or medicines [19].

In the UK, regulation aligns with standards set by the European Food Safety Authority (EFSA), which requires pre-market safety assessments and authorisation for new bacterial strains [19,20]. However, demonstrating efficacy remains a challenge, increasing development costs and limiting approved health claims [8]. Due to these regulations, EFSA are yet to approve any health claims for probiotic food products and have only accepted one claim for the prebiotic native chicory inulin [20]. In the US, regulatory framework allows structure-function claims (for example, 'supports digestive health') to be made without pre-market authorisation, although disease-related health claims still require formal approval [19].



The animal microbiome

What are the similarities and differences between microbiomes in humans and animals?

Animal and human microbiomes have many parallels, including the body sites they inhabit, such as the gut, mouth and vagina [19].

However, there can be significant differences between animal and human microbiomes. For example, *Bifidobacteria* species dominate the bacterial gut community in breastfed infants as they thrive on special sugars (oligosaccharides) found in human breast milk [30]. *Bifidobacteria* species play a key role in training the infant immune system [30]. In horses, foals transition quickly from milk to a fibre-based diet from 3 weeks old [31]. As a result, fibre-utilising bacteria, such as *Treponema* species, rather than milk-utilising *Bifidobacteria*, become dominant in the foal hindgut microbiome [31]. In fact, the foal hindgut microbiome reaches an adult-like composition at around 2 months old [31].

As with humans, every animal hosts a unique microbiome [32]. Microbiomes vary greatly across the diverse range of animal species, each reflecting their unique evolutionary history and relationships with humans and the environment [32,33].

Companion animals have close relationships with their owners, sharing the same environment and often engaging in frequent physical contact [34]. This dynamic facilitates the exchange of microbiota between humans and animals [34]. Pet ownership has been linked to greater human skin microbiome diversity, with research suggesting that early exposure to animals may lower a child's risk of developing asthma [9].

Many animals ingest soil as part of their natural behaviour, which directly contributes to the diversity of their gut microbiome [9]. For example, in sheep and cattle, soil-derived micro-organisms are estimated to make up as much as 3% of the rumen microbiome [9].

What are the benefits of researching animal microbiomes?

The similarities between animal and human microbiomes lead to an overlap in their research and applications. For example, the study of animal microbiomes can lead to applications in human immune health, mental health disorders, dietary interventions and antimicrobial stewardship [32]. There is also substantial potential in developing species-specific prebiotics and probiotics, which could lead to more effective treatments, improved animal welfare and biodiversity conservation [2,33,35].

Benefits of modifying microbiomes in animals

Livestock: Administering host-specific probiotics can modulate the gut microbiome composition in buffalo calves, significantly improving performance and gut health [36].

Companion: People living with companion animals have an increased abundance of beneficial bacteria, such as *Lactobacillus*, which supports gut health [37].

Wildlife: Supplementing the diet of the critically endangered Australian southern corroboree frog with carotenoids altered their skin microbiome, significantly increasing both bacterial abundance and species richness. Since the skin microbiome of amphibians plays a key role in defence against pathogens and disease, this study demonstrated that dietary manipulation could help protect endangered amphibious species by increasing their resilience [38].

What are the main challenges for microbiome research in animals?

There is a lack of funding for basic microbiome research in animals [39]. As a result, prebiotics and probiotics originally developed for humans are often re-purposed for animal healthcare, despite differences in beneficial gut micro-organisms [35]. There is limited evidence supporting the efficacy of many probiotics currently administered to animals, such as horses [35]. In some cases, the use of human-targeted probiotics in animals has even been linked to adverse health outcomes [40].

Animal microbiome science is not well-integrated into veterinary courses, which means it is often overlooked in clinical practice. Researchers also face significant barriers in accessing samples, as UK regulations restrict sample collection to licensed vets to safeguard animal welfare [41]. This has often contributed to a disconnect between vets and researchers, hindering progress in the field.

Conclusion

Advances in microbiome science hold transformative potential across many sectors, including healthcare, environmental sustainability and agriculture. However, research and funding in the microbiome field has been disproportionately directed towards humans. Bacteria also dominate microbiome research and applications, while other important micro-organisms, such as fungi and viruses, are overlooked.

It is essential that microbiomes are recognised for their influence across humans, animals and the environment. To ensure that microbiomes research and applications have maximum impact on society and are incorporated into other research streams to maximise their potential, there is an urgent need to foster collaboration between researchers, funders, industry, healthcare professionals, regulators, policymakers and end-users. Only by countries, disciplines and sectors all coming together can we get the most out of microbiome research: driving innovation and promoting balanced outcomes across human, animal and environmental health.

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