Crop microbiome and sustainable agriculture

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A global assessment of the structure and function of the crop microbiome is urgently needed for the development of effective and rationally designed microbiome technologies for sustainable agriculture. Such an effort will provide new knowledge on the key ecological and evolutionary interactions between plant species and their microbiomes that can be harnessed for increasing agriculture productivity.

The global demand for food is expected to increase by 70% by 2050 to feed the increasing human population[1]. However, current agricultural practices are unlikely to meet this requirement in the face of continued land degradation, reductions in soil fertility, changing climate and increasing extreme weather events. In addition, there are growing economic (for example, high cost of production or low margin of profitability), social (for example, consumers desire for chemical-free food), environmental (for example, minimizing water and air pollution) and policy (for example, the green deal of the European Union (EU)) demands for innovative approaches that can simultaneously promote crop productivity and environmental sustainability[2]. Consequently, multiple intergovernmental organizations (for example, Food and Agriculture Organization of the United Nations (FAO)) and academic societies (National Academy of Science) have recommended the development of innovative natural products that complement conventional farming practises to ensure the sustainable provision for food and fibre[1,3].

Harnessing microorganisms associated with crop species (the crop microbiome) has been postulated as one of the most promising long-term solutions to the integral challenges of achieving food security, while supporting a healthy environment[2,3]. These microorganisms are responsible for resource availability, plant health, and resilience to biotic and abiotic stresses. The global recognition of the functional potential associated with the crop microbiome has generated substantial public and private investment in microbial-based products aiming to complement conventional farming and to increase farm productivity. Consequently, agricultural microbial products are among the fastest-growing industries globally, increasing at an annual rate of 17%, with an anticipated market value of ~US$12 billion by 2026[4]. Conversely, it is predicted that demand for chemical-based products (currently a ~US$250 billion industry), particularly pesticide usages, is expected to decline owing to emerging regulatory requirements and consumer demand for food with low chemical residues. For example, the EU has set a goal to replace 50% of chemical pesticide usage with biological solutions by 2030[5].

Crop microbiome

Although both soil and plant microbiomes have important roles in crop performance and yield, we argue that tools developed based on plant microbiomes, including endophyte (microorganisms that live inside plant tissues) and rhizosphere (soil associated with crop roots) microbiomes, have a greater chance of success compared with those that utilize bulk soil (soil that is not attached to the crop root) microbiomes. The greater chance of success of using plant microbiomes is driven by eco-evolutionary interactions between plant species and their microbiomes (Supplementary text box). These include selection pressure driven by the requirement of metabolic coupling of the microbiota with the chemical diversity of root exudates in the rhizosphere and the subsequent filtration effect caused by plant-immune systems in the endosphere, which allows the enrichment of only a few microbial groups. In addition, the intimate physical connection between plants and their microbiomes that elicits a larger impact on plant performance, and the availability of tools to manipulate them (for example, seed dressing or tissue culture), is likely to support the realization of crop-microbiome based approaches[2,6]. New scientific knowledge of the core microbiome of crop (that is, a subset of the plant microbiome that is consistently associated with a particular crop species under all environmental conditions and that is considered to have co-evolved to provide critical host functions) could be utilized to develop effective tools from plant microbiomes, bioactive metabolites and a combination of microorganisms and metabolites to promote plant productivity[7]. However, to realize the full potential of the crop microbiome to support productive

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and sustainable croplands would require a better understanding of the structure and function of the crop microbiomes, and of their interactions with host species across the globe and soil types at a level similar to the Human Microbiome Project.

Current challenges

Current use of microbial inoculants has proved useful to address some agronomic challenges; however, large-scale adoption remains low mainly owing to inconsistency in the efficacy under different environmental conditions[7,8]. This inconsistency is driven by scientific and technological issues, including lack of colonization and/or expression of phenotypes, competition with indigenous soil microflora, lack of mutual plant–microorganism recognition and plant-driven selection. The successful application of microbiome technologies to farming systems requires addressing these fundamental knowledge gaps. These include advancement in our understanding of the key members and functional capabilities of the crop and its core microbiome; eco-evolutionary processes that govern assembly, dynamics and stability of the crop microbiome (for example, via domestication processes); plant–microbiome interaction networks and communication pathways that influence crop productivity in a range of environmental conditions; and the influence of the microbiome on host genotype, phenotype and health that ultimately regulate crop productivity. Similarly, current technical gaps constraint translation outcomes of the current products, including lack of effective products and application techniques that promote effective colonization of introduced microbiota, and the effective tools to manipulate the microbiome in situ to attract and maintain activities of beneficial microbiomes[2,6,8,9]. In addition, some regulatory (registration and safety requirements) and social (for example, public perception and acceptance) risks remain constraints that need proactive management to help future commercialization and adoption successes.

Solutions

Microbial products are expected to substantially contribute to increased farm productivity, resilience to global change, profitability and sustainability, while considerably reducing chemical inputs. However, achieving this expectation will first require multiple and complimentary approaches to deliver innovative solutions and tools, including the development and implementation of microbiome-based products and tools by targeting the core microbiome of crop species, ensuring products are compatible with the host and its microbiome; innovate approaches for rationale microbiome engineering in situ through the use of biochemical (for example, signal molecules that attract beneficial microorganism), genetic (for example, plant breeding, gene editing to harness genomic trait that attract beneficial microorganisms) and microbial (microbiota that stimulate activities of other beneficial microorganisms) tools; and adopting an interdisciplinary systems-based approach to ensure integration of microbiome tools in conventional farming. These scientific and technological advances should be accompanied by the development of policies aiming to ensure global economic fair-play (for example, Nagoya protocol), training and resourcing the farmers. In addition, policy, public and commercialization risks can be managed with effective communication and with focus on long-term visions rather than short-term outcomes. In this respect, globally coordinated scientific and policy approaches are essential. Although new efforts to study and provide baseline data for global crop microbiomes (Global Initiative of Crop Microbiome and Sustainable Agriculture, which was established to advance our knowledge on the eco-evolutionary drivers of the structure and function of the crop microbiome worldwide (Supplementary text box)) and to harmonize international policies (International Bioeconomy Forum) are in progress, these initiatives either need to be substantially expanded or many more similar initiatives to be established to provide efficient solutions. If these issues are systematically addressed, new plant microbiome tools can bring potentially step change improvement in farm productivity and profitability, growth of microbial industries and the sustainability of our environment

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Competing interests
The authors declare no competing interests.

Supplementary information
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