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Editorial: Maximizing nitrogen fixation in legumes as a tool for sustainable agriculture intensification, volume II

María Florencia Del Papa[1*], María Jesús Delgado[2], Pilar Irisarri[3], Fernando Alfredo Lattanzi[4] and Jorge Monza[3]

[1]Instituto de Biotecnología y Biología Molecular (IBBM), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Dep. Ciencias Biológicas, Facultad de Ciencias Exactas, Universidad Nacional de La Plata (UNLP), La Plata, Argentina, [2]Experimental Station of Zaidín, Spanish National Research Council (CSIC), Granada, Spain, [3]Department of Biología Vegetal, Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, [4]Área de Pasturas y Forrajes, Instituto Nacional de Investigación Agropecuaria (INIA), Colonia, Uruguay

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Davey Jones,
Bangor University, United Kingdom

*CORRESPONDENCE
María Florencia Del Papa
floppy@biol.unlp.edu.ar

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Editorial on the Research Topic
Maximizing nitrogen fixation in legumes as a tool for sustainable agriculture intensification, volume II

Introduction

Estimations indicate that there will be nearly 10 billion people on Earth by 2050. Then agriculture will be required to generate about 50% more food because of the rise in the world population (FAO, 2017). The great challenge for agricultural systems is to provide secure food for the growing world population while maintaining or improving soil and water quality, together with working towards the mitigation of climate change without exceeding planetary boundaries (Wanyenze et al., 2023). This can be achieved through sustainable agriculture intensification and involves increasing current levels of production while minimizing impacts on the environment.

Nitrogen (N) availability is one of the most crucial factors that limit plant growth and development, both in natural ecosystems and in agronomic systems where nitrogen is mainly provided as fertilizer. However, its use is limited by the high cost of production and the toxicity of chemical fertilization. The massive use of nitrogen fertilizers had a strong positive impact on agricultural productivity. As a result, the global demand for nitrogen fertilizers has steadily increased. Unfortunately, on the other hand, higher N inputs are associated with higher N surpluses, which are in turn often linked to negative environmental consequences if not incorporated in soil organic matter, contributing to greenhouse gas emissions (N_2O), ozone depletion (NO), and water pollution (NO_3^-). Furthermore, N volatilization (NH_3) may contribute to eutrophication of neighboring systems. N management must therefore play a central role in the sustainable transformation facing global food production (Ying et al., 2017; Leip et al., 2021). This implies that alternative strategies should be applied to maximize the availability of agronomic resources and optimize crop yields (Cassman and Dobermann, 2021; Leip et al., 2021).

N fertilizers are a primary global N source to agroecosystems but have a large CO_2 footprint. The second largest source of supplying N to agroecosystems is biological nitrogen fixation (BNF) driven by a symbiotic relationship between legumes and soil bacteria collectively known as rhizobia. The symbiotic relationship between soil rhizobia and legumes generates root nodules where rhizobia uses plant photosynthates to convert atmospheric N_2 into NH_3 through their nitrogenase enzyme, providing this biologically useful nitrogen to the plant. The N_2-fixing capacity benefits not only legume plants themselves but also other coexisting species in mixed pastures or intercropped crops, as well as subsequent crops, thus reducing the need for synthetic N fertilizers.

The biochemical, genetic, and evolutionary aspects of the symbiotic interaction have been extensively reviewed over the years (Jones et al., 2007; MacLean et al., 2007; Gibson et al., 2008; Oldroyd and Downie, 2008; Masson-Boivin et al., 2009; Downie, 2010; Oldroyd et al., 2011; Hawkins and Oresnik, 2022). Improving the effectiveness of the BNF process has been the focus of research for many decades. It is a current major goal within the sustainable use of soils, which is one of the worldwide challenges of the time. This Research Topic complements/extends the previous Volume I (Irisarri et al., 2021), addressing different approaches directed toward the exploitation of the symbiosis between legumes and rhizobia as a helpful tool to develop more sustainable agricultural systems. The understanding of the BNF process will increase our capacity to design sustainable diversified agroecosystems through the inclusion of legumes.

This Research Topic

Cover crops can provide several economic and environmental services to agroecosystems, reducing for instance the use of agrochemicals (Zemmouri et al., 2022). In this Research Topic, Berriel and Perdomo compared the performance of six tropical legumes (*Crotalaria juncea, Crotalaria spectabilis, Crotalaria ochroleuca, Cajanus cajan, Dolichos lablab, Mucuna pruriens*) and the temperate legume *Glycine max*. They showed that cover crops based on *C. cajan* and *G. max* contributed significantly to N input through BNF. Particularly, *C. cajan* demonstrated high levels of FBN without the need for rhizobia inoculation, even in soils with no previous history of this crop.

To reduce the impact of abiotic stress in different crops, it is increasingly imperative to isolate and characterize microorganisms that help plants cope with adverse conditions. *Vicia faba* minor (L.) is a cool-season, annual grain legume crop traditionally used as a protein source for human and livestock diets (Gu et al., 2020). Fogelberg et al. interactions between faba bean cultivars and *Rhizobium* sp. strains and its impact on the yield of subsequent spring wheat crops. Inoculation of Rhizobium did contribute nitrogen to the system but had no effect on the yield or protein content of faba beans or following spring wheat yields under Swedish field conditions.

Soybean (*Glycine max* (L.) Merr.) is economically the most important grain legume worldwide (FAO, 2017). The leading producers of soybean are the USA, Brazil, and Argentina. For European countries, there are a range of incentives to decrease soybean imports and expand local soybean production. Unlike genetically modified soybean imported from the Americas, soybean grown in Europe would be non-genetically modified and thus command a higher price. In this Research Topic, Maluk et al. evaluated the feasibility of growing early maturity group soybean varieties in the high latitude of northern UK and showed that soybean requires inoculation of introduced *Bradyrhizobium* to benefit from BNF because there are no native soybean-nodulating bacteria in these soils. In addition, they assess whether introduced bradyrhizobia inoculant could persist in Scottish soils, and what the impact of their widescale introduction and subsequent naturalization might be on the microbiome present in current arable soils.

In African countries, the subsistence of legume farmers can benefit from inoculation with exotic rhizobia, but usually they do not have access to commercial inoculants. In this Research Topic, Pudasaini et al. showed that root nodules can be harvested and crushed onto legume seeds, increasing both nodulation and plant chlorophyll content under field conditions. Consequently, nodule crushing represents a straightforward practice to spread elite rhizobia strains. This decentralized technology could also allow smallholders to improve indigenous strains or indigenize exotic strains by reiterated nodule crushing from healthy plants.

Failures in *Medicago sativa* (alfalfa) production have been attributed to low soil pH and the presence of inefficient parasitic rhizobia strains (Eardly et al., 1992; Del Papa et al., 1999; Eardly et al., 2022). This group of rhizobia generically, known as the Oregon-like strain, are competitive for nodulation of alfalfa in acid soils but exhibits low symbiotic efficiency. The genomic analysis of Oregon strain LPU83 allowed the assignation to the novel species *Rhizobium favelukesii* (Torres Tejerizo et al., 2016). In this Research Topic, Berais-Rubio et al. characterized alfalfa inefficient rhizobia strains isolated from plants grown in acid soils in Uruguay and confirmed the presence of *Rhizobium favelukesii* strains and evaluated their competitiveness. Their findings support the necessity for inoculating in areas where inefficient strains are likely to be present. Also, they reported that homologous genes that codify for M16-like peptidases (HrrP and SapA) were found in the genomes of *R. favelukesii* strains ORY1, Or191, and LPU83 which can to some extent explain the parasitic behavior of this *Rhizobium* species.

To decrease the impact of acid soils on alfalfa crops, it is necessary to use elite microorganisms with high performance that help plants cope with adverse conditions, including the presence of inefficient parasitic rhizobia strains. Among the criteria for choosing strains as alfalfa inoculants, their tolerance to and persistence in acid soils should be contemplated. Cafiero et al. presented an in-depth genomic analysis of *Sinorhizobium meliloti* LPU63, which is a strain isolated from an acid soil in Argentina that showed outstanding competitiveness, persistence, and efficiency in acid and neutral conditions. The information regarding LPU63 activities compatible with plant-growth promotion phenotypes, together with the presence of the complete denitrification pathway that could be related to moderate N_2O emissions, constitute the basis of future trials toward the design of new bioinoculants for environmentally sustainable alfalfa production.

Concluding remarks

Despite significant progress being made in various areas, there is still a long road ahead to achieve the ambitious goal of completely replacing synthetic N- fertilizers with BNF. The analysis of interactions between plants and microbes remains challenging. In the short term, research efforts to advance on novel molecular approaches, such as meta-omics and genome editing, are required to explore and integrate broader knowledge of host-specific plant-microbe interactions.

It will be essential to generate new approaches (e.g., rhizobia inoculation techniques) and select rhizobia strains and/or multi-bio inputs formulations for efficiency and competitive ability. In addition, the effects of environmental factors on the complexities of plant-microbial signaling and understanding of the intricacies of BNF are also necessary. Finally, the improvements of the symbiosis efficiency by specific plant-host associations in addition to approaches to incorporate BNF into non-legume crops is another important challenge.

Author contributions

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