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Review

Use of commercial bio-inoculants to increase agricultural production through improved phosphorus acquisition

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ABSTRACT

Meeting increasing global demand for food, fibre, and bioenergy requires efficient use of finite resources, and presents a key sustainability challenge to the agricultural industry, scientists and policy-makers. Increased interest in low-input agriculture in recent years has seen the growing development and use of commercial biological inoculants (bacteria and/or fungi) to increase the mobilisation of key nutrients, especially phosphorus (P), and enhance their availability to crop plants. Here, we review the terminology, composition and function of bio-inoculants and the many factors which impact on their efficacy for increasing P availability in different soil and plant environments. We conclude that the beneficial attributes of commercial bio-inoculants for integrated production systems are not clearly defined. Evidence to support their effectiveness is currently confounded by inadequate quality standards and insufficient knowledge of the underlying mechanisms, which have led to contradicting reports on field performance. There is, however, scope to engineer specific inoculant formulae for more sustainable P management in different system-soil-plant combinations, provided future research is properly structured to help understand the complexity and dynamism of microbial functioning and interactions in soils.

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1. Introduction

Phosphorus (P) makes up ~0.7% of the earths' crust, making it the eleventh most abundant element (Schwedt, 2001). It is an essential element for plant growth and hence is widely applied as inorganic fertiliser for agricultural purposes; global P fertiliser consumption for 2010 was approximately 37.6 Mt and is expected to increase to 42.3 Mt in 2014, with an annual 3% increase in demand thereafter (Heffer and Prud'homme, 2010). Reserves of mineable rock phosphate (RP), which provide the base raw material for inorganic fertiliser production, are however relatively small and finite (current global reserves estimated at ~260 billion tonnes, mostly in North Africa) and may only last for 100–400 years (Van Kauwenbergh, 2010; Cordell and White, 2011). Over 80% of RP reserves are utilised for fertiliser production since RP is the only source from which fertilisers can be made in large quantities. Future scarcity of RP may threaten future global food security, particularly so in areas which do not have any RP reserves (e.g. most of Europe). As the economic exploitation of RP becomes more difficult, the cost of P fertilisers will also increase, putting further pressure on agricultural profitability and rural livelihoods.

This potential crisis is exacerbated by the increased agricultural production that will be required to meet future global demand for feed, fibre, bioenergy and food. Since this enhanced demand is largely expected to be met through yield gains on existing lands (Heffer and Prud'homme, 2010), this will require greater inputs of nutrients, including P. This practise already appears to be occurring in rapidly developing countries; for example, fertiliser consumption in Asia has increased more than 10-fold in the past 40 years (Sattari et al., 2014). In addition to resource concerns, the generous use of P fertilisers (and other industrial uses of P, for example in washing powders) has created widespread economic, social and environmental problems associated with eutrophication (Dodds et al., 2009). Much of the P applied to agricultural land in the past is now stored in the soil as surplus P. This not only undermines current attempts to reverse the ecological damage and loss of aquatic biodiversity caused by eutrophication, but is also a potentially unutilised P resource, termed legacy P, that could be used to reduce applications of costly inorganic (manufactured) fertilisers, without affecting crop yields (Sattari et al., 2012; Sharpley et al., 2013; Withers et al., 2014).

Strategies to reduce reliance on, and make better use of, inorganic P include recovery and use of P from human and livestock waste streams, optimising the application of P fertiliser and better exploitation of existing soil P reserves (Elser and Bennett, 2011; Cordell et al., 2011; Withers et al., 2014). However, the exploitation of soil P reserves is hindered by the fact that the forms, distribution and accessibility of legacy P are complex and diverse, and often not in a form that is readily available for plant uptake. The potential store of legacy soil P is large. Withers et al. (2001) calculated that an average ca. 1000 kg ha^{-1} of surplus P is stored in UK soils in the productive arable and grassland areas. Cumulative P inputs in European cropland for the period 1965–2007 were also vastly in excess of off-take, with totals of approximately 1115 kg ha^{-1} applied, compared to off-takes of 360 kg ha^{-1} (Sattari et al., 2012). If legacy P was accounted for in nutrient planning, it has been estimated that this could reduce the requirement of inorganic fertiliser by 50% (Sattari et al., 2012).

The inclusion of biological inoculants (hereon referred to as 'bio-inoculants') within integrated nutrient management aims to reduce inorganic fertiliser inputs by helping to exploit legacy P reserves. The global market for bio-inoculants is growing at an estimated rate of ~10% per annum (Berg, 2009); valued at $440 million in 2012 and expected to reach $1,295 million by 2020 (Transparency Market Research, 2014). Demand is primarily driven from Asia, where governments, such as China and India, are promoting the use of bio-inoculants through tax incentives, tax exemptions and grants to provide support for their manufacture and distribution. However, it is remarkably difficult to determine the effectiveness of commercial bio-inoculants which are claimed to promote plant growth; dozens of microorganisms, used alone and in combination, are claimed to promote crop yields but in most cases the underlying mechanisms responsible for these beneficial effects are unknown. Furthermore, quality control procedures within the industry and accepted standards to allow product comparison etc. are generally lacking. It is therefore timelier than ever to elucidate the effectiveness and mode of action of bio-inoculants.

Here we review the potential benefits of using commercial bio-inoculants designed to promote plant growth, with an emphasis on P supply through the exploitation of legacy P reserves. We provide a clarification of the nomenclature and classification of bio-inoculants within the broader plethora of terms used to describe "bio-fertiliser"-type products. Finally, we examine the effectiveness of commercially available bio-inoculants on both grass and cereal production, which account for the overwhelming proportion of land used for agricultural purposes.

2. Soil phosphorus and plant uptake

Plant-available phosphorus concentrations in the soil solution are inherently low (Marschner, 1995). Soil P is most conveniently considered as having two origins (Withers et al., 2014): native P, which is released into the soil solution by natural weathering of the soil parent material (primary minerals; Fig. 1), and legacy P (Sharpley et al., 2013), the result of past applications of fertilisers and manures. As of 2000, P inputs (fertilisers and manures) across industrialised countries globally were 31 Tg $year^{-1}$, while outputs were 19 Tg $year^{-1}$, resulting in a P surplus of 12 Tg $year^{-1}$ (Bouwman et al., 2011). In the UK alone, the 2013 P surplus has been calculated to be 87 Gg (DEFRA, 2014), a 7.2 kg ha^{-1} surplus (Fig. 1). This poses an additional environmental risk from run-off or leaching (Fig. 1). Global soil P surpluses continue to grow and could rise to as much as 18 Tg $year^{-1}$ by 2050 (Bouwman et al., 2011). Changes to farm management could reduce P surpluses by 20%, e.g. shifting from beef to poultry, or solely arable systems to mixed arable and livestock, and improving manure management (Bouwman et al., 2011). There is also potential for bio-inoculants to reduce P inputs by exploiting the accumulating P surpluses in the soil.

The release of legacy P into the soil solution depends on the form in which it is predominantly held, but it appears to be more plant-available than native P (Johnston et al., 2014). Plant uptake studies have shown that the inorganic mono/divalent phosphate ion, $H_2PO_4^-$ and HPO_4^{2-}, constitutes the bulk of plant P assimilation; and although there is some evidence of plant uptake of DNA (nuclease-resistant analogue of DNA) (Paungfoo-Lonhienne et al., 2010), generally the organic P forms must be mineralised; a process mediated by enzymes, chiefly phosphatase and phytase (enzymatic dissolution).

In the absence of a pool of readily-available P provided by inorganic fertilisers, plants must utilise numerous strategies to acquire soil inorganic (P_i) and organic (P_o) quickly and efficiently to