



## A Biofertilizer Should Be Judged at Harvest, Not on an Agar Plate

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The first decision in biofertilizer research is usually taken at the laboratory bench, where an investigator must judge which of many isolates is promising enough to justify further work. The final decision belongs elsewhere: a microbial product earns an agronomic recommendation only when evidence shows that it benefits a crop under growing conditions that can be identified and reproduced. Between those two decisions lies the most consequential stretch of the entire research pipeline, and too often the least thoroughly examined. Laboratory screening answers a question that is necessary but deliberately narrow. A clearing zone around a colony shows how one organism behaves toward one supplied substrate in one defined medium, while assays for phytohormone synthesis, siderophore production or tolerance to salinity, heat and desiccation offer further, if indirect, clues about what that organism might accomplish in association with a plant. None of these assays, however refined, measures a benefit delivered to a crop growing in soil. To deliver that benefit, the organism must remain viable through formulation, storage and application; it must encounter the seed, root or leaf at the place and developmental stage where its activity matters; it must establish and stay active within a resident microbial community that is typically far larger and better adapted to local conditions; and it must act on a resource or constraint that genuinely limits the performance of that crop in that field. These requirements form a chain in which each link must be tested on its own terms, because a positive result at one stage cannot be presumed from a positive

result at the stage before it, and a strain that excels on the plate may falter anywhere between the incubator and the harvest.

Phosphorus offers the clearest illustration of why that chain matters. Solubilizing an insoluble phosphate in culture does not establish that an inoculant will increase phosphorus acquisition by a crop in the field, and a meta-analysis of phosphate-solubilizing bacteria spanning 104 articles and 506 individual treatments shows why the distinction is far more than academic. Inoculation produced an overall positive effect on phosphorus uptake and on root and shoot biomass, yet improved uptake did not consistently translate into greater plant height or biomass, and the authors pointed to inappropriate phosphorus sources in isolate screening, together with a possible lack of rhizosphere competence, as reasons why strains selected for vigorous solubilization in vitro so often fail to deliver consistently under practical conditions [1]. The agronomic logic is simple: even a genuine gain in phosphorus uptake will not raise biomass or yield when the crop is limited by water, by another nutrient or by some other condition, so the proposed mechanism and the promised crop outcome must be measured separately rather than inferred one from the other. None of this argues against microbial inputs. On the contrary, the most successful inoculants strengthen the case for demanding field evidence. In replicated small-plot maize trials, the phosphorus-solubilizing fungus *Penicillium bilaiae* increased yield in 66 of 92 trials, with a statistically significant mean gain of 0.17 t/ha, or

1.8%, while in 295 of 369 larger field trials the gains were both higher and less variable, averaging 3.5% [2]. A global meta-analysis of biofertilization built on 171 peer-reviewed publications likewise reported positive average yield responses, although their size depended strongly on climate, ranging from about 20% in dry climates to 8.5% in continental ones [3]. Such studies confirm that microbial inputs can be genuinely useful. They also demonstrate why the magnitude, consistency and context of a field response, rather than the diameter of a halo or the intensity of a colorimetric reaction, must govern any recommendation.

Averages, however reassuring, conceal the distributions from which they are drawn, and it is the distribution rather than the mean that an individual farmer actually experiences. In on-farm experiments spanning 54 Swiss fields, the growth response of maize to inoculation with arbuscular mycorrhizal fungi ranged from 12% below to 40% above the uninoculated comparison. What makes that study especially instructive is that the spread was far from random: soil microbiome indicators predicted 86% of the variation in growth response, and the abundance of pathogenic fungi, rather than nutrient availability, proved the single best predictor of whether inoculation would succeed [4]. A two-season field evaluation of a commercial foliar inoculant based on *Methylobacterium symbioticum* in maize offers a more sobering counterpoint. Dry-matter yield was numerically higher with the product but not significantly different from the untreated control, the authors' own estimates of biologically fixed nitrogen fell roughly fourfold from the first season to the second, and they concluded that a commercial product should provide an unequivocal and quantitatively relevant contribution to plant nutrition, which this one did not appear to do [5]. The defensible conclusion from such evidence is neither that biofertilizers invariably work nor that they generally fail. Their performance is conditional, and heterogeneity of this kind is information rather than noise. Treating it as error to be averaged away discards precisely what a farmer needs to know, whereas identifying the conditions under which a product succeeds or fails is itself a scientific result of direct practical value.

This recognition should reshape how efficacy trials are conceived. The operative question is not merely whether treated plots out-yielded untreated ones, but what benefit a product claims, against which practical alternative, and with what degree of reliability. Where the claim concerns nutrient acquisition,

tissue nutrient concentrations and total uptake must be measured alongside harvest data. Where the claim is fertilizer saving, an inoculated crop receiving a reduced fertilizer rate must be compared with an uninoculated crop receiving that identical reduced rate, while a full conventional fertilizer treatment provides the benchmark against which any claim of maintained yield is judged; without the first comparison, the tolerance of the crop to lower inputs is easily mistaken for the contribution of the microbe. Where the claim is drought resilience, the experiment must first demonstrate that water stress actually occurred and must then determine whether any early advantage in vigor or physiology survived to harvest. Comparisons of this kind prevent a favorable shift in one convenient measurement from being presented as proof of a broader agronomic benefit. Product quality belongs to the same argument. A trial reveals little about an organism's field potential if its identity, viable dose or condition at application is uncertain, and a product cannot be presumed effective simply because its microbes survived storage. Every trial should therefore document the strain, formulation, dose and method of application, and should relate crop responses to soil properties, crop variety, fertilizer management and weather rather than reporting a single treatment mean in isolation. Testing across locations and seasons allows researchers to estimate both the expected size of the benefit and the likelihood that it will recur, which is the quantity on which a farmer's purchasing decision ultimately rests. Within this framework, a neutral result is no embarrassment. Properly documented, it maps the conditions under which application offers little advantage, and that map is as valuable to an extension system as any record of success.

For agricultural universities, which stand at the junction between microbiology and extension, this discipline opens a more credible and ultimately more valuable path from strain to recommendation. A strain need not be promoted for every crop and every soil to be worth developing, and a product that delivers a modest but repeatable benefit in a clearly defined situation may well be preferable to one associated with a striking laboratory result and an uncertain field record. Recommendations issued on this basis would specify the crop, the soil and agroclimatic conditions, the method and timing of application, the outcome actually measured and the limits of the evidence on which the advice rests. Precision of this kind does not weaken a recommendation. It gives farmers a sound basis for deciding whether an input is worth purchasing

and applying, and it protects the credibility of biofertilizers as a category from the erosion that follows every product that promises more than it delivers. Agar plates will remain indispensable for revealing microbial possibilities, and nothing in this argument diminishes their place at the outset of an investigation. Their proper role is to begin the inquiry, not to conclude it. The decisive work lies in determining which candidates retain their activity after formulation, function in real soils under real management and deliver a benefit that remains evident when the crop is harvested and weighed. Biofertilizers will earn lasting credibility only through that complete chain of evidence, and a research community that insists on it will find farmers, extension agencies and funders far more willing to trust what it recommends.

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