

Zinc-Solubilising Bacteria From Rice Rhizosphere and Their Effect on Seedling Vigour

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ABSTRACT

Zinc deficiency limits rice on many flooded and alkaline soils and shapes the zinc content of a grain that feeds a large part of the world, so bacteria that make soil zinc available to the crop have drawn steady interest. This mini review looks at what is known about zinc-solubilising bacteria from the rice rhizosphere and their effect on early seedling growth. It draws on published work on zinc chemistry in soil, on the mechanisms of solubilisation, on screening assays, and on reports from rice and other cereals, and it presents no new data. Organic acids, proton release and chelating compounds are the usual explanations, and many isolates also make auxin or siderophores, so the cause of any seedling response is hard to assign. The central difficulty is that a clear zone on a plate is a poor predictor of what an isolate does in soil or in a plant, because the insoluble zinc source, the medium, the pH and the sugar supply are all unlike a flooded paddy. Doubts about the persistence of an introduced strain and inconsistent effects across soils and cultivars add to the problem. The review concludes that rice-associated zinc solubilisers are a reasonable source of candidates, that an effect on seedling vigour is plausible but not firmly established, and it sets out the assays, controls and reporting that would make future claims comparable.

Keywords: Zinc-solubilising bacteria; Rice rhizosphere; Seedling vigour; Zinc biofortification; Plate assay; Plant growth-promoting rhizobacteria; Mini review

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Article Class: Mini Review

1. Introduction

Rice feeds a large part of the world, and a grain that is thin in zinc passes the shortfall on to people whose diets lean heavily on it. Zinc deficiency is recognised as a human health problem in its own right [1], and estimates built on national food supplies suggest that the risk is widespread [2]. Raising the zinc content of staple crops, whether by breeding or by management, is one of the routes that has been proposed [3]. Rice is grown on flooded fields from monsoon Asia to southern

Europe, so the problem is not confined to one region.

Soil is the other half of the story. Total zinc in a field can be ample while the fraction a plant can take up is small, and soil properties such as pH, carbonate and organic matter decide how much is available [4]. Flooded rice soils add their own chemistry, and the interplay of reduction, pH and precipitation has made zinc one of the more common limiting nutrients in lowland rice [5]. Fertiliser zinc is one answer. Bacteria that release

zinc from insoluble forms are another, and they have attracted attention because they could, in principle, work with the soil instead of adding to it. The aim is a fair account of what has been shown and what has merely been repeated.

This mini review looks at zinc-solubilising bacteria that have been isolated from the rice rhizosphere and at what is known about their effect on early seedling growth. The question sounds simple, and the answer is less so. A bacterium that clears a halo around itself on a plate is not necessarily a bacterium that helps a seedling, and the gap between those two events is where most of the uncertainty sits. We describe the mechanisms, the assays, the evidence from rice and related cereals, and the reasons a promising screen so often fails to translate. The article is a narrative review and reports no new data.

2. Literature Review

2.1 Zinc in Soil, Rice and Seedlings

Zinc is a structural and catalytic component of many plant proteins and is needed in small but steady amounts for growth [6]. Plants differ widely in how well they cope when it is scarce, through changes in root growth, exudation and internal handling of the element [7]. A young seedling is particularly exposed: its seed reserves are being drawn down, its root system is small, and it has not yet had time to explore much soil. Early zinc supply is therefore a plausible limit on how fast a seedling establishes.

Zinc deficiency in rice has a recognisable chemistry. In a flooded soil the element can be held in forms that roots cannot easily use, and these depend on pH, on the carbonate and sulphide present, and on the organic matter [4, 5]. Agronomic biofortification, that is, raising grain zinc through fertiliser and soil management, has been reviewed for cereals as a practical complement to breeding [8, 9]. Any microbial approach has to be judged against that background, since it is competing with a fertiliser that already works.

2.2 The Rice Rhizosphere as a Source of Isolates

The rhizosphere is the thin zone of soil shaped by the root, and it supports a community far richer than the bulk soil beside it [10]. Plant-associated bacteria that promote growth have been reviewed repeatedly [11, 12], and the rice root is no exception. Work on the microbiomes of rice found that the community changes from the soil to the root surface and to the interior of the root, and

that the root itself shapes what colonises it [13]. This is the logic for sampling the rice rhizosphere when hunting for zinc solubilisers: a strain that has lived beside rice roots may be better suited to them.

The logic has limits. A rhizosphere isolate has survived in the conditions of the sampling site, and those conditions rarely match the field where the strain is later used. The same study that described the rice root communities also showed that the site and the compartment sampled mattered [13], which is a reminder that a strain from one paddy is not a strain from every paddy. This is why the same isolate can look excellent in one laboratory and unremarkable in the next.

2.3 How Bacteria Mobilise Zinc

Microorganisms change the availability of metals in several ways: they release organic acids and protons, they make compounds that bind metals, and they alter redox conditions [14]. For zinc, the explanation most often offered is acidification through organic acids. A diazotrophic bacterium was shown to dissolve several insoluble zinc compounds, with acid production among the proposed explanations [15], and a bacterium isolated from the air of a tannery was reported to solubilise zinc salts [16]. Reviews gather the mechanisms and the plants affected [17]. The parallel with phosphate solubilisation is close, and much of the method was borrowed from it [18].

Table 1 sets the routes side by side, and Figure 1 shows where they act. Two points follow. First, several of them do not release zinc at all: auxin production, for instance, changes root growth and is a classic feature of growth-promoting bacteria [12, 19], so an isolate that carries both traits can improve a seedling for reasons unconnected to zinc. Second, the assays used to detect each route measure something narrower than the route itself. A siderophore test reports a chelator in general [20], not a chelator that binds zinc in soil. Which of these routes dominates in a given isolate is seldom established, and it is often simply assumed.

2.4 Screening Assays and What They Report

Almost every study begins with a plate. A medium is amended with an insoluble zinc compound, the isolates are spotted, and a clear zone around a colony is taken as solubilisation. The format is a direct descendant of the phosphate medium developed for screening phosphate-solubilising microbes [21], and later broth tests measure released zinc and medium pH. Colorimetric tests for auxin follow an old method [22] and are widely used to flag a second trait. Figure 1 shows where

each of these traits sits in the soil, microbe and root picture.

Table 1. Proposed routes by which bacteria mobilise zinc, and how each is usually inferred.

Route	What it is thought to do	Usual evidence
Organic acids	Lower local pH and bind zinc, freeing it from solid phases [14, 15]	Clear zone; acid detected in broth
Proton release	Acidifies the zone around the cell [14]	Medium pH drop
Chelating compounds	Hold zinc in a soluble complex [14, 20]	Siderophore assay; rarely tested against zinc itself
Auxin and root effects	Do not release zinc, but enlarge the root and the zone explored [19, 22]	Colorimetric indole test
Uptake effects on the plant	Change root surface and transport, not soil zinc [12]	Pot trial with controls

Note: Qualitative summary of mechanisms discussed in the cited literature; routes often act together in one isolate.

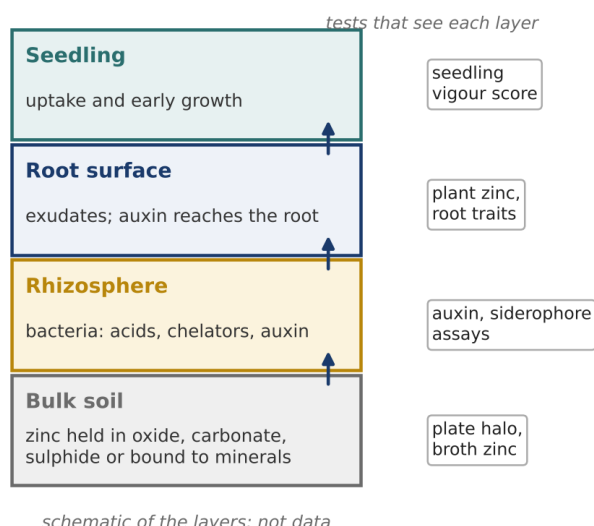


Figure 1. Layered view of zinc, microbe and root at the rice rhizosphere (schematic, not data).

The choice of the insoluble source matters more than is often admitted (Table 2). Zinc oxide, carbonate and phosphate are the common choices [15, 16], and each rewards a slightly different behaviour. The criticism raised for tricalcium phosphate in phosphate screening, that one insoluble source is not an adequate universal selector [23], applies in spirit to zinc as well. An isolate selected on oxide is selected for its ability to acidify a medium, and acidification on a sugar-rich plate is not the same as acidification in a flooded soil. Incubation time and the number of replicate plates per isolate are seldom stated either, which makes a repeat test hard to plan. Stating how much zinc the medium carried is a small step that makes comparison far easier. It is a

habit worth keeping even when the answer seems obvious from the plate.

Table 2. Insoluble zinc sources used in screening and what each can reward.

Source	What a clear zone may mean	Main caution
Zinc oxide (ZnO)	Any acid-producing cell can dissolve it [15, 16]	Rewards acidification, whatever its origin
Zinc carbonate (ZnCO ₃)	Acid or chelation [15]	Reacts to the medium; carbonate is common in alkaline soil [4]
Zinc phosphate (Zn ₃ (PO ₄) ₂)	May overlap with phosphate solubilisation [18, 21]	Mixes two traits in one read-out
Zinc sulphide (ZnS)	Closer to reduced paddy soil [5]	Used less often; slow to read

Note: Comments are qualitative; behaviour depends on medium, pH and sugar supply and is not a measured property of the isolates.

3. Materials and Methods

3.1 Scope and Question

The review asks one question in two parts: do zinc-solubilising bacteria from the rice rhizosphere plausibly improve early seedling growth, and how well does a plate-based solubilisation result predict that outcome? The question was divided into the sub-questions an experiment would need to answer: where the isolate came from, how solubilisation was measured and against which source, whether other plant-growth traits were present, how the plant response was assessed, and whether the strain was tracked. None of these checks is difficult, but each is easy to skip when a screen is already producing exciting colours.

3.2 Literature Assembly

The review draws on peer-reviewed work in four areas: the chemistry and plant biology of zinc; the ecology of the rhizosphere; the mechanisms and assays of microbial zinc solubilisation; and reports on inoculation of rice and other cereals. Sources were chosen for relevance, standing in the field and clarity of method. Work on other crops, such as maize, wheat and soybean, is used for what it teaches about assays and plant response, not as evidence that the same effect occurs in rice.

We did not run a formal systematic search and we do not claim one. This is a narrative synthesis, and the selection reflects the authors' judgement. It is therefore a better guide to how to read this literature than to the size of any particular effect, and it avoids quoting figures from individual studies that could not be checked against the primary papers for this article. Choosing sources

this way is a compromise between breadth and the time available to read each one carefully.

3.3 Appraisal Framework

To judge how far a report could be trusted, we used four questions. Was solubilisation tested against more than one insoluble source and with the medium described [23]? Was the plant response tested in soil, with the native microbial community present, or only in sterile conditions [24]? Was the introduced strain followed so that an effect could be linked to it [25, 26]? And was seedling vigour assessed with more than one criterion [27]? Table 3 lists the gaps we looked for and what a complete report would include.

4. Results

4.1 What Isolates Show on the Plate

The reports agree on one thing: zinc-solubilising bacteria are not rare. Isolates have been described from the rice rhizosphere, including an *Acinetobacter* strain studied for its zinc-solubilising potential [28], and from the rhizospheres of maize [29, 30], wheat [31] and soybean [32]. Many of the isolates belong to a small number of genera, and *Bacillus* appears often in the cereal and legume work [30, 32]. That recurrence may reflect real ecology, or it may reflect that the plates select for fast, acid-producing, spore-forming organisms. Whether a genus is common because it is useful or because it is easy to isolate is hard to tell from the reports alone.

Most plate results are reported as presence or absence of a clear zone or as a ratio of zone to colony. These are convenient and they are also crude. A strain that produces a large halo on oxide may do little on carbonate, and the reverse. Broth tests that measure dissolved zinc and pH give a quantitative picture, but they too depend on the source, the medium and the incubation time [15, 16]. The point is not that a study is poor, only that its result travels less far than its abstract suggests.

4.2 What Happens in Seedlings and Pots

Pot and seedling tests are where the effect has to appear. In rice, inoculation with zinc-solubilising bacteria has been reported to improve growth and zinc nutrition [33], and root-associated *Bacillus* was reported to improve growth, yield and zinc translocation in basmati varieties [34]. Endophytic microbes isolated from a zinc hyperaccumulator improved rice growth and grain zinc in another study [35]. Work on wheat and maize, and on soybean and wheat together, points in a similar direction [30, 31, 36, 37].

The reports share a caution. Many experiments are carried out in pots, often with sterilised or amended soil, over a limited time, and with seedling traits that can be affected by several bacterial products at once. A study of soil zinc release, soil available zinc and plant zinc content for selected isolates illustrates how many variables have to be tracked before an effect can be attributed to the solubilisation trait [38]. Figure 2 sketches which questions can be answered at which level of testing, from plate to field. Short trials are cheap and quick, which is part of their appeal and part of the problem.

Seedling vigour deserves a note of its own. It is a composite idea, and it has long been assessed by combining several criteria instead of relying on one [27]. A study that reports shoot length alone cannot say much about vigour, and one that reports a vigour score without describing how it was built cannot be compared with the next. A seedling grown a few days longer can tell a rather different story from one harvested early.

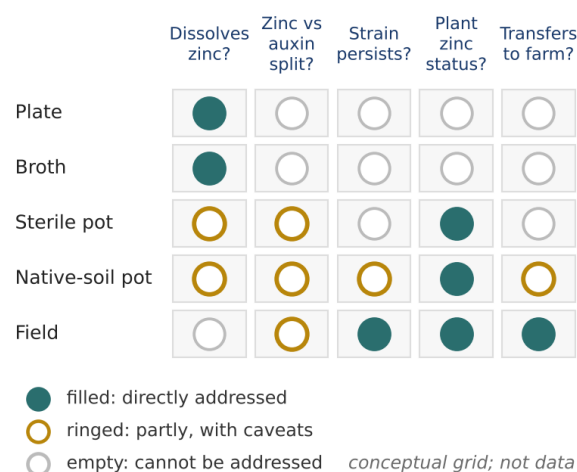


Figure 2. Qualitative grid of what each test level can and cannot show (conceptual matrix, not data).

4.3 Why the Plate Does Not Travel

Several reasons recur in the methodological literature, and they are summarised in Table 3. A plate has a defined, usually generous, supply of sugar and a single insoluble source, while soil offers a mixture of zinc forms, low and fluctuating carbon, and a crowd of competitors. Reviews of inoculation emphasise that introduced strains must compete with the resident community and that effects are often hard to reproduce [24, 26]. Formulation and quality of the inoculant add a further layer of variation [25]. A strain grown on sugar in a flask meets a very different world when it reaches a paddy field.

Soil chemistry can also blunt the effect. Where zinc is held in carbonate or other stable phases,

the supply that a bacterium can mobilise depends on pH and on the buffering capacity of the soil [4, 5]. An acid-producing bacterium in a strongly buffered soil may change the pH very little, and one in a flooded soil faces a quite different chemistry from the aerobic plate. None of this means the isolate does nothing; it means the plate could not have told us. A benefit that vanishes in unsterilised soil is not one a farmer would ever see. A grower reading a trial report wants to know one thing: would this have worked in my field?

Table 3. Why a plate result may not carry to the seedling, and what to report.

Gap	Consequence	What to report
Single insoluble source	Isolate ranking depends on the source [23]	Two or more sources, with pH of the medium
Rich medium, much sugar	Acid from sugar use, not from soil [23]	Medium composition; a soil-based test
Sterile pot, no competitors	Effect may vanish in native soil [24]	Soil type and sterility; native comparison
Strain not tracked	Cannot link the effect to the strain [25, 26]	Recovery or marker evidence
Auxin not separated	Growth effect not tied to zinc [19]	Auxin and zinc supply measured together
One cultivar, one soil	Effect does not generalise [7]	Cultivar and soil, with replicates

Note: Summarised from the cited methodological and inoculant literature; not attributed to any single study.

4.4 Persistence and Inconsistency

A bacterium that cannot persist near the root cannot deliver a sustained benefit. Reviews of inoculant technology describe how survival depends on the carrier, the formulation and the soil, and how field results are frequently variable [25, 26]. Studies of the impact of inoculants on resident communities add that the outcome depends on the soil and the strain [24]. For zinc solubilisers the available reports rarely follow the introduced strain through the season, so a gain in seedling growth cannot be tied to the inoculant itself.

Inconsistency across soils and cultivars is the other side of the same coin. Cultivars differ in zinc efficiency [7], and the same bacterium can be helpful with one and neutral with another. Reports from different laboratories, using different media, soils and plants, cannot be pooled without caution. When a positive result is described, it is worth asking how many comparable tests did not make it into print. The differences are small one by one, yet they decide whether a result can be repeated. Read this way, a null result from a small pot trial is

not proof that an isolate does nothing.

Put plainly, the literature supports a cautious statement. Zinc-solubilising bacteria are common in the rice rhizosphere, many solubilise insoluble zinc in the laboratory, and several reports describe better growth or zinc status of rice and other cereals after inoculation. How far a plate result predicts a field effect, and how much of a seedling response is due to zinc and not to auxin or other traits, is not settled by evidence we can cite with confidence. That is a modest statement, and it is the one the literature can currently bear.

4.5 Reading a Claim of Benefit

A reader meeting a claim that a bacterial isolate improved rice seedlings can ask a short series of questions. Which insoluble zinc source and which medium were used, and was the pH recorded [23]? Were auxin, siderophore and other traits measured, so that the zinc effect can be separated from the rest [19, 20]? Was a non-inoculated control run in the same soil, and was a heat-killed or non-solubilising bacterial control included? Was the strain recovered at the end? A report that answers all four is uncommon, and one that answers none should be read as an observation instead of evidence of effect.

Figure 3 sets out the path from isolate to claim. Each step removes some candidates, and the final step, a repeatable effect in a soil of the intended type, is the one most often missing. Claims about biofortification of the grain deserve extra care, since a seedling response says little about zinc in the mature grain [5, 9].

5. Discussion

5.1 Interpretation and Practical Reading

The main conclusion of this review is a conditional one. Zinc-solubilising bacteria from the rice rhizosphere are a sensible place to look for inoculant candidates, and some have been reported to improve growth or zinc status. But a clear zone on a plate is a screening result and not a prediction, and treating it as one has probably inflated expectations. The question for a grower is not whether a bacterium dissolves zinc oxide but whether it changes the zinc supply to a seedling in a soil like theirs. That distinction sounds fussy until a grower pays for a product on the strength of a halo. The same logic explains why two laboratories can screen one strain and reach opposite conclusions about it. Nothing here argues against using these bacteria; it argues for measuring what they do.

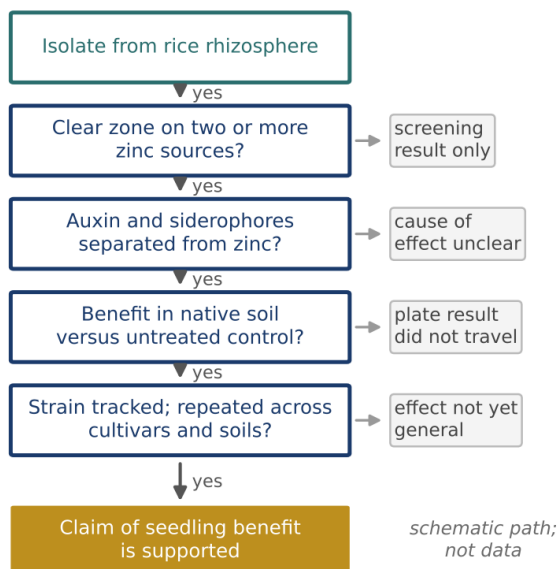


Figure 3. Decision path from isolate to a claim of seedling benefit (schematic, not data).

A second reading concerns causes. Because many isolates combine zinc solubilisation with auxin production, siderophores or other traits [12, 19], a seedling benefit cannot be credited to zinc without experiments that separate them. That does not make the benefit less real. It does change what a farmer can expect when the soil is not short of zinc, since a growth effect that works through the root might still appear, and one that works through zinc might not.

Three findings would change this reading. A repeatable seedling benefit in a soil with adequate available zinc would suggest a mechanism other than zinc supply. A clear link between isolate ranking on a plate and plant response across several soils would justify the plate as a screen. And a demonstration that an introduced strain persists near the root through a season, alongside an effect, would strengthen the causal case [24, 26].

5.2 Limitations

This is a narrative review and shares the limits of that form. The selection of sources reflects judgement, no formal search or quality scoring was done, and the review does not quote numerical results from individual studies, because these could not be checked against the primary reports for this article. A reader who needs an effect size should consult the original papers, applying the appraisal questions above.

The review also draws on work from maize, wheat and soybean to understand assays and plant responses, and these crops differ from rice in root biology and soil. Flooded rice soils in particular behave differently from aerobic ones [5]. We have

used the other crops to frame hypotheses, and the conclusions should be read in that light. Reviews of this kind help more when they say where the evidence stops than when they smooth it over.

5.3 Implications for Study Design

A study that could settle the question would screen isolates against more than one zinc source and describe the medium, then test promising ones in the soil type of intended use, with and without the native community. It would measure auxin and siderophore production, include non-solubilising bacterial controls, record the strain's fate with a marker or a specific detection method, and use more than one cultivar. Seedling vigour would be assessed by several criteria [27], and zinc status of the plant would be measured directly.

Reporting matters as much as design. Giving the composition and pH of the medium, the zinc source, the soil properties and the inoculum size allows a later reader to compare results [25]. These requirements are demanding, but they are what separates a result a grower can use from one that supports a hunch. Even a small study can be useful if it is open about its soil, its medium and its controls.

5.4 Directions for Future Work

Three needs stand out. First, comparisons of several plate formats against pot and field outcomes for the same isolates, to learn which screen, if any, predicts a plant response. Second, work that separates zinc effects from root-growth effects, for example by testing zinc-adequate and zinc-poor soils side by side. Third, field-scale studies that track the introduced strain and report grain zinc as well as seedling traits, since biofortification is the ultimate aim [3, 8]. These points apply with equal force to any other plant-associated inoculant. The tools are simple; the difficulty is the discipline to use them.

6. Conclusion

Zinc-solubilising bacteria are common in the rice rhizosphere, and some of them plausibly help a seedling establish. The evidence, as we can responsibly summarise it, does not yet establish how often that happens, how large the effect is, or how much of it is due to zinc. What the literature does show is why a plate result travels poorly, which controls would make a claim credible, and what a fair report contains. Readers should treat claims of large benefit with caution until they meet those standards.

For the practitioner the message is practical rather than discouraging. A candidate isolate can

be tested, provided that the soil is described, the strain is tracked and an untreated control is kept. For the researcher, the opportunity is a set of comparable, soil-based studies that turn a promising screen into a measured result growers can rely on.

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9. Conflict of Interest

The authors declare no conflict of interest.

10. Author Contributions

Q.R. conceived the review and wrote the sections on the rhizosphere and screening assays. V.M. wrote the sections on zinc chemistry and plant response. F.G. wrote the sections on inoculant persistence and study design. All authors revised the manuscript and approved the final version.

11. Ethics Statement

This is a review of published literature. No human participants or animals were involved and no ethical approval was required.

12. Data Availability

No new data were generated. All sources are cited in the reference list.

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