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Chapter 3

Nutrient Delivery to Woody Plants by Stem Injection: A Critical Appraisal of Transport Mechanisms, Agronomic Efficacy and Physiological Cost

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Abstract

Nutrient disorders in perennial woody crops and amenity trees are frequently refractory to soil fertilisation because calcareous or alkaline substrates immobilise applied micronutrients, and to foliar sprays because several elements move poorly once deposited on the leaf surface. Stem injection, the direct introduction of solutions into functional xylem through a port in the trunk, has been proposed for more than nine decades as a way of bypassing both bottlenecks. Interest has intensified as injection hardware developed for pesticide and antibacterial delivery has become commercially available, yet the nutritional application has never been subjected to the same critical scrutiny as the plant-protection application. This review examines the physiological basis, delivery technology, agronomic evidence and physiological cost of stem injection used specifically for nutrient delivery. Literature was identified through structured searching of scholarly bibliographic indexes accessible during preparation, supplemented by backward citation searching, and appraised for design adequacy, controls, measurement validity and generalisability rather than scored with a formal instrument. Four conclusions emerge with differing degrees of confidence. Correction of iron deficiency chlorosis by injected ferrous sulphate is the best-supported application, replicated across several genera and reported to persist for more than one season, although most trials are small, short and conducted on severely chlorotic trees. Evidence for zinc, manganese and boron is thinner, is

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often confounded with co-injected fungicidal compounds, and includes documented failures to reach critical leaf concentrations. Macronutrient delivery is constrained by a mass-balance problem that no reported injection protocol resolves, and the single well-documented magnesium trial found the approach ineffective. Injection ports impose a reproducible wound whose consequences depend on host compartmentalisation capacity, dose and pressure, and are rarely followed for long enough to quantify cumulative cost under repeated annual use. The dominant unresolved question is not whether injected nutrients enter the tree, which is well established, but whether the delivered dose reaches deficient tissue in a spatially uniform and physiologically meaningful quantity at acceptable cost to the stem.

Keywords: Trunk injection; endotherapy; xylem transport; iron deficiency chlorosis; micronutrient correction; wound compartmentalisation; perennial tree nutrition.

1. Introduction

Perennial woody plants present a nutritional problem that annual crops largely avoid. A tree occupies the same rooting volume for decades, so any chemical property of that volume which restricts nutrient availability becomes a chronic rather than a seasonal constraint. On calcareous and alkaline substrates, high pH and elevated bicarbonate concentrations render applied iron compounds rapidly unavailable, and the resulting deficiency chlorosis is among the most persistent nutritional disorders of orchard and amenity species worldwide (Ahmadi et al., 2023; Morales et al., 1998). Similar although less severe constraints affect zinc and manganese availability, and the practical result is that repeated soil applications may fail to alter leaf composition even when the applied quantity greatly exceeds crop removal.

Foliar spraying is the conventional alternative, and it is not without value, but it carries its own limitation. Several elements move only slowly out of the tissue on which they are deposited, so re-greening is often restricted to the sprayed surface and repeated applications are required within a season. The combination of an ineffective soil route and a partially effective foliar route defines the practical opening that stem injection has been proposed to fill. Stem injection, also described as trunk injection or endotherapy, introduces an aqueous formulation directly into functional xylem through a port drilled or driven into the trunk, from which the transpiration stream distributes it through the crown (Archer et al., 2022; Benigno et al., 2025). Because the applied material never contacts soil colloids and never has to traverse the root plasma membrane or the leaf cuticle, the two principal chemical barriers to conventional fertilisation are circumvented in a single operation.

The idea is old. Systematic experimental injection of solutions into woody stems was consolidated as a physiological method by the late 1930s, and the technique was applied to nutritional questions almost immediately (Roach, 1939). Controlled injection of iron salts was reported to correct lime-induced chlorosis of fruit trees in the mid-1930s (Wallace, 1935), and injection of borax solutions was used in the same period to manipulate the boron status of apple (*Malus domestica*) (Askew & Chittenden, 1936). A second wave of activity followed the development of pressure injection equipment in the 1970s, when injection rate, port geometry and the influence of wood anatomy were characterised for the first time in a systematic way (Sinclair & Larsen, 1981; Worley et al., 1976; Worley & Littrell, 1981). A third and much larger wave began after 2010, driven not by nutrition but by the search for delivery routes for systemic pesticides and antibacterials against phloem-limited and vascular pathogens, most conspicuously huanglongbing of citrus and emerald ash borer of *Fraxinus* species (Archer & Albrecht, 2023a; Hu & Wang, 2016; Sadof et al., 2022; Tanis et al., 2012).

That third wave has transformed the technical landscape without resolving the nutritional question. Injection hardware is now commercially mature, ranging from single-use low-pressure capsules through spring-loaded injectors to prototype mechanised systems mounted on orchard vehicles (Ojo et al., 2024; Toth et al., 2025). Distribution of injected compounds within the crown has been quantified with radiolabelled and analytically traceable tracers (Aćimović et al., 2014; Mota-Sanchez et al., 2009; Tanis et al., 2012). Wound response has been characterised by destructive autopsy and by repeated non-destructive observation (Aćimović et al., 2016; Doccola et al., 2011). Almost none of this work concerns nutrients. The physicochemical properties that govern the fate of an injected pesticide, principally moderate water solubility and low reactivity with wood constituents, differ substantially from those of a concentrated inorganic salt solution, and it cannot be assumed that conclusions transfer between the two classes of solute.

The existing review literature reflects this imbalance. Comprehensive treatments of stem injection published over the past decade are organised around plant protection, discuss nutrients only in passing, and generally treat nutrient delivery as an established secondary application rather than as a claim requiring evidential support (Archer et al., 2022; Benigno et al., 2025; Berger & Laurent, 2019; Shang et al., 2024). Reviews focused on a single pathosystem are narrower still (Li & Nangong, 2022). Reviews of iron chlorosis correction, conversely, are organised around soil and foliar strategies and typically mention injection as a historical curiosity or a last resort without appraising the primary trials (Ahmadi et al., 2023). The result is that a practitioner deciding whether to inject a micronutrient into a declining orchard has no synthesis that assembles the relevant primary evidence, weighs its methodological quality, and states honestly where the evidence stops.

Recent HLB-focused studies have continued to expand the plant-protection evidence base across orchard-scale performance and whole-tree response, reinforcing the contrast between the rapidly developing protection literature and the comparatively sparse nutrition-specific evidence (Castellano-Hinojosa et al., 2024; Albrecht et al., 2025; Buzzi et al., 2026).

There is a second and less obvious gap. The nutritional and the plant-protection literatures have developed largely independent accounts of the same physical process. Work on pesticide distribution has established that spatial uniformity within the crown depends strongly on the number and arrangement of injection ports, and that transport in the trunk combines vertical ascent with radial diffusion in a spiral pattern (Aćimović et al., 2014). Work on wound response has established that the injury imposed by a port is compartmentalised successfully by healthy trees but that the extent of internal damage scales with applied pressure (Archer & Albrecht, 2023a; Doccola et al., 2011). Neither body of evidence has been brought systematically to bear on nutrient injection, where the delivered solute is chemically reactive, the required dose is set by whole-canopy demand rather than by a toxicological threshold at a feeding site, and the treatment is likely to be repeated annually over the productive life of the tree.

1.1 Scope, Research Gap and Objectives

This review is bounded to the delivery of mineral nutrients into the stems of woody plants for the purpose of correcting or preventing nutrient disorders, improving nutrient status, or altering yield and product composition through nutrient supply. The relevant hosts are dicotyledonous trees and shrubs with secondary xylem, together with arborescent monocotyledons of horticultural importance whose trunk anatomy differs fundamentally and which are therefore treated as a separate analytical case. Injection of pesticides, antibacterials, antibiotics, growth regulators, nucleic acids and plant defence activators falls outside the scope except where such studies provide mechanistic evidence about transport, distribution, dose control or wound response that bears directly on nutrient delivery. Injection into herbaceous stems and pseudostems is excluded except as a boundary case that illuminates the anatomical limits of the technique. Soil and foliar fertilisation are treated only as comparators.

The specific gap addressed is the absence of a critical synthesis that separates what is demonstrated from what is assumed in the nutrient application of stem injection. Three claims recur in the applied literature and in commercial practice without proportionate evidential support: that injection reliably raises the nutrient status of the whole canopy rather than of the sectors served by the injected xylem; that the quantities deliverable through a stem port are agronomically meaningful for elements required in large amounts; and that the wound cost is negligible under the repeated annual application that a chronic deficiency would require. Each claim is examined against the primary evidence.

The objectives are, first, to establish the physiological and anatomical constraints that determine what stem injection can and cannot achieve for solutes of different chemical character; second, to compare delivery technologies with respect to dose control, distribution uniformity and injury; third, to appraise the agronomic evidence element by element and host by host, distinguishing replicated findings from single reports and giving explicit weight to negative results; fourth, to evaluate the wound cost and its dependence on host, dose and pressure; and fifth, to identify where the evidence is strong enough to support practice, where it is not, and what study designs would resolve the difference. The intended contribution is a nutrition-specific critical appraisal that imports the mechanistic rigour of the plant-protection literature into a domain that has not yet received it, and that states the limits of current knowledge without overstating either promise or futility.

2. Methods for Literature Selection

2.1 Review Design and Rationale

A critical narrative review was selected in preference to a systematic review, scoping review or meta-analysis because the underlying evidence base is structurally unsuited to the alternatives. The relevant primary studies span nine decades, use incompatible outcome measures ranging from visual chlorosis scores through chlorophyll meter readings to leaf elemental concentrations and fruit yield, apply doses expressed variously as solution concentration, mass per tree and volume per metre of canopy diameter, and are distributed across horticultural, arboricultural, forestry and soil science literatures with different reporting conventions. Quantitative pooling would generate a spurious impression of comparability. A scoping review would map the literature without evaluating it, which is precisely the deficiency this review seeks to remedy. A systematic review with documented screening counts was not attempted because complete coverage of the older arboricultural and extension literature could not be assured from the sources accessible during preparation, and reporting counts that imply exhaustive retrieval would misrepresent the search.

The narrative form does not license reduced transparency or reduced appraisal. The review was conducted with reference to established criteria for narrative review quality, which require an explicit statement of purpose and target audience, justification of the article's importance, description of the literature search, referencing of statements to evidence, appropriate presentation of the data, and scientific reasoning appropriate to the strength of that data (Baethge et al., 2019). The search strategy, eligibility criteria, screening approach and appraisal criteria are stated in full below, and interpretive limitations are declared in the final section.

2.2 Information Sources

Searches were run in the following bibliographic resources, each of which was genuinely queried during preparation: Crossref Metadata Search, accessed through its public programmatic interface, which provided the primary route to horticultural, arboricultural and forestry records and to complete bibliographic metadata; and Europe PMC, which indexes biomedical and life-science records including those from MEDLINE, and which provided coverage of the plant-pathology and plant-physiology literature. General web-based scholarly searching was used to locate abstracts, to identify records not surfaced by the two indexes, and to resolve metadata discrepancies. No search was performed in subscription citation indexes, and no claim is made regarding their coverage; the practical consequence is discussed under Limitations.

Database searching was supplemented by backward citation searching of the reference lists of recent reviews and of primary studies retrieved in the first pass, which was the principal route by which pre-1970 sources and older arboricultural reports were identified. Forward searching was approximated through the retrieval of recent articles citing the major methodological papers. Bibliographic verification was performed against digital object identifier registration records and, where these were incomplete or contained evident transcription errors, against the article landing pages of the issuing journals. Every retained reference was checked for author list, title, year, journal, volume, issue, pagination or article number, and identifier resolution before inclusion.

2.3 Search Strategy and Search Period

Search concepts were constructed from four facets. The intervention facet combined the terms trunk injection, stem injection, endotherapy, trunk implantation, microinjection and pressure injection. The substrate facet combined nutrient, micronutrient, macronutrient, fertiliser and the names of individual elements and their common injected salts and chelates, including iron, ferrous sulphate, zinc, zinc sulphate, manganese, boron, borax, calcium, magnesium, potassium, nitrogen, urea and phosphite. The host facet combined tree, woody plant, orchard, and the common and scientific names of the principal injected genera. The outcome facet combined chlorosis, leaf mineral content, chlorophyll, uptake, translocation, distribution, yield, fruit quality, phytotoxicity, wound and compartmentalisation.

Facets were combined with Boolean operators in the form (trunk injection OR stem injection OR endotherapy OR trunk implantation) AND (nutrient OR micronutrient OR iron OR zinc OR boron OR manganese OR calcium OR magnesium OR potassium OR nitrogen) AND (tree OR woody OR orchard OR palm), with the outcome facet added in a second pass to retrieve mechanistic and injury studies, and with the intervention facet run alone against transport and wound-response terms to capture the plant-protection literature bearing on distribution and injury. Additional targeted strings paired the intervention facet with individual host genera and with device and automation terms.

Database searches covered the period from 1 January 1970 to 10 June 2026. The starting year was selected because systematic pressure injection of nutrients into orchard and landscape trees, with characterisation of injection rate and port geometry, dates from the early 1970s and constitutes the beginning of the technically continuous literature. Foundational earlier publications that establish the physiological method and the first nutritional applications were retrieved through backward citation searching and retained where they remain conceptually necessary. The final search date was 10 June 2026.

2.4 Eligibility Criteria

Peer-reviewed original research articles and peer-reviewed review articles were eligible. Studies were included when they reported the introduction of a mineral nutrient, or of a formulation containing one, into the stem, trunk or main scaffold of a woody plant, and reported at least one measured outcome relating to uptake, internal distribution, tissue nutrient concentration, physiological status, growth, yield, product composition or injury. Studies of non-nutrient solutes were included only where they contributed mechanistic evidence on transport, distribution uniformity, device performance or wound response. Comparative studies in which injection was contrasted with soil or foliar application were prioritised, as were studies reporting untreated or water-injected controls.

Publications were excluded when they concerned herbaceous species without secondary growth, except where used as an explicit anatomical boundary case; when they addressed injection solely for pest or disease control without transport, dose or injury data of mechanistic relevance; when they were conference abstracts, extended abstracts or single-page proceedings items without sufficient methodological detail for appraisal; when they were trade publications, commercial technical bulletins, patents, unrefereed opinion pieces or unverifiable items; and when bibliographic identity could not be confirmed. Preprints were not used where peer-reviewed evidence on the same question was available. No geographical restriction was applied. Only publications available in English were assessed, which is a substantive restriction given that parts of the older nutritional injection literature appear in other languages.

2.5 Screening, Duplicate Handling and Study Selection

Records retrieved from each source were screened first by title and, where the title was uninformative or ambiguous, by abstract. Records passing this stage were assessed against the eligibility criteria using the abstract and, where the abstract was absent or insufficient, the full text or the fullest available bibliographic and descriptive record. Because the retained set is small and was assembled iteratively rather than through a single fixed protocol, no screening counts are reported; presenting such counts would imply a systematic selection process that was not undertaken.

Duplicates arising from overlapping index coverage were identified by digital object identifier and, where identifiers differed, by matching author list, title and pagination. Several records were encountered under more than one identifier, and in each case the identifier resolving to the version of record on the publisher's landing page was retained. Where indexes disagreed on publication year, author name spelling or title wording, the metadata were reconciled against the registration record and the landing page, and the corrected form was adopted. Sources whose full text could not be obtained were retained only where the abstract or bibliographic record supported the specific claim for which they are cited, and claims were phrased so as not to exceed what that record substantiates; sources that could be neither obtained nor verified were discarded.

2.6 Critical Appraisal and Evidence Synthesis

No formal risk-of-bias instrument was applied, because the retained studies do not share a design family for which a recognised tool exists and because the older reports do not contain the information such tools require. Appraisal instead proceeded against explicit criteria selected for their relevance to this literature: presence and nature of the control, in particular whether a wound-only or water-injected control was included; replication at the level of the tree rather than the branch or leaf; duration of observation relative to the expected persistence of the treatment; validity of the outcome measure, with direct elemental analysis of tissue weighted above visual scoring and chlorophyll meter readings weighted between the two; adequacy of dose reporting; whether the injected formulation contained a single nutrient or a mixture whose components could not be separated; the severity of the initial deficiency, which determines the scope for a detectable response; and the geographical and taxonomic concentration of the evidence.

Themes were developed inductively from the retained set rather than imposed in advance. Preliminary reading identified four recurrent axes of disagreement or uncertainty: whether distribution within the crown is uniform enough to justify whole-tree conclusions; whether the deliverable quantity is agronomically meaningful for a given element; whether observed responses are attributable to the injected nutrient or to co-injected compounds and to the wound itself; and whether the injury cost is acceptable under repetition. These axes structure the synthesis. Where studies disagree, the explanation was sought first in design differences, then in host anatomy, then in formulation chemistry, and only afterwards attributed to genuine biological variation. Confidence in each conclusion is stated explicitly and calibrated to the number of independent studies, the consistency of their findings, and the adequacy of their controls.

3. Physiological Basis and Constraints of Xylem-Mediated Nutrient Delivery

The apparent simplicity of stem injection conceals a set of physical and chemical constraints that determine, before any agronomic question is asked, which elements can plausibly be delivered this way and to which parts of the tree. Understanding these constraints is a prerequisite for interpreting the agronomic literature, because several apparent contradictions in that literature resolve into differences in host anatomy or solute chemistry once the transport problem is stated properly.

3.1 Transport Pathway and the Transpiration Dependence of Distribution

An injected solution enters the xylem lumen and is thereafter carried by the same tension-driven ascent that moves soil-derived water. The immediate consequence is that uptake rate is not controlled by the injection device beyond the initial phase but by the tree's own transpiration. Injection of an apoplastic tracer and of rubidium chloride into olive (*Olea europaea*) demonstrated that injected solutions move principally upward through the older xylem rings and that uptake is directly governed by transpiration rate, with a single port sufficient to distribute solution through a scaffold of eight centimetres diameter but two ports required for a trunk of seventeen centimetres (Navarro et al., 1992). This is the foundational observation for the whole field, and it has two implications that are frequently overlooked in applied work. Uptake will be slow or incomplete whenever transpiration is low, which includes early spring before full leaf expansion, periods of water deficit when stomata are closed, and trees whose crowns are already thin from the disorder being treated. Trees in the worst nutritional condition, which are the trees most likely to be injected, are therefore the trees least able to take up an injected solution promptly.

The dependence on transpiration also implies that the injected solute follows the same spatial pattern as sap flow, and sap flow in a tree trunk is not uniform. Sap flux density varies systematically with depth into the xylem and differs between trunk and branches, and this radial profile changes with irrigation regime and with xylem anatomical characteristics (López-Bernal et al., 2010; Nadezhdina et al., 2007). A port that intersects a highly conductive band will deliver solution to the sectors of the crown supplied by that band; a port a few centimetres away, or at a different depth, may serve a substantially different set of branches. This is the mechanistic basis for the sectoriality that has been repeatedly observed with tracers. The tracer evidence is unambiguous on this point, although it comes almost entirely from pesticide studies. Quantification of trunk-injected imidacloprid in apple crowns showed that spatial uniformity increased significantly with the number of injection ports, that four ports allowed uniform spatial distribution, and that uniform and non-uniform patterns were established early and persisted throughout the experiment; the concentration patterns indicated transport by vertical uptake with a spiral component combined with radial diffusion (Aćimović et al., 2014). Radiolabelled imidacloprid injected into *Fraxinus* species likewise showed spatially and temporally structured rather than homogeneous distribution (Mota-Sanchez et al., 2009; Tanis et al., 2012). Earlier work using dye in elms established the same qualitative point, that the entry route determines the pattern of internal distribution (Holmes, 1982). The practical inference for nutrition is direct: a single-port nutrient injection cannot be assumed to have treated the whole canopy, and leaf samples taken without reference to port position may substantially misrepresent the treatment received by the tree as a whole.

Whether this inference transfers fully from pesticides to nutrients is not established, and the uncertainty deserves emphasis. Imidacloprid is a moderately water-soluble organic molecule with limited reactivity toward wood constituents. A concentrated ferrous sulphate solution is neither. Inorganic cations injected into xylem encounter an apoplast rich in exchange sites, and the composition of xylem sap is itself under physiological control and varies seasonally (Takamatsu et al., 2023). Retention of injected cations on cell wall exchange sites near the port would reduce the effective transport distance relative to a neutral organic solute, making sectoriality worse rather than better. No study has quantified this comparison directly, and the assumption that pesticide tracer patterns describe nutrient behaviour should be treated as a working hypothesis rather than an established result.

3.2 Xylem Architecture, Sectoriality and Species-Specific Injectability

The capacity of a stem to accept an injected volume varies systematically among taxa, and this variation was characterised early. Wood characteristics related to the injectability of trees were shown to differ markedly between species, establishing that vessel diameter, vessel length, porosity class and the presence of tyloses or resin all bear on whether a given device can deliver a given volume in a workable time (Sinclair & Larsen, 1981). Ring-porous species with long, wide earlywood vessels accept solution readily but concentrate flow in the outermost growth ring, whereas diffuse-porous species distribute flow across a greater radial depth but at lower flux per vessel.

Conifers present the most severe case. Injection of seven coniferous species with pressurised water capsules showed that in resinous species uptake was slow and sometimes incomplete, particularly in spring when resin secretion was high, and that uptake rate declined with smaller injector diameter (Sánchez-Zamora & Fernández-Escobar, 2004). The same study reported that rubidium was recovered in all sampled tree sections of Spanish fir (*Abies pinsapo*), that healthy trees took up more and faster than unhealthy ones, and that distribution in conifers, although slower than in angiosperms, was more uniform. This is an important and underused finding, because it identifies a genuine trade-off rather than a simple ranking: the anatomy that makes conifers difficult to inject is the same anatomy that makes their distribution more even once injection succeeds. It also reinforces the concern raised above, since the reduced uptake of unhealthy trees was demonstrated directly.

Arborescent monocotyledons constitute a separate case that cannot be treated by analogy with dicotyledonous trees. Palms possess scattered vascular bundles within a parenchymatous ground tissue rather than a continuous cylinder of secondary xylem, they lack a vascular cambium, and they therefore cannot compartmentalise and occlude an injection wound in the way that a dicotyledonous tree does. Reviews of the technique have noted explicitly that the structure and arrangement of vascular tissue in palm trunks is fundamentally different from that of true trees and is likely to affect the distribution of injected material (Archer et al., 2022). The consequence is that evidence generated in palms should not be used to support practice in dicotyledonous trees, or the reverse, and this review treats the two separately.

3.3 Element-specific Behaviour After Delivery

Reaching the leaf is necessary but not sufficient. Once an element is deposited in leaf apoplast or symplast, its subsequent usefulness depends on whether it can be redistributed to tissues formed later, and this differs sharply among elements. Boron provides the clearest illustration. Boron is conventionally described as phloem-immobile, but its mobility is species dependent and is determined by the presence of sugar alcohols capable of forming stable boron complexes; isolation and characterisation of soluble boron complexes established the mechanism by which boron becomes phloem-mobile in species that accumulate polyols (Hu et al., 1997). The practical implication for injection is that a single boron injection may be redistributed to developing organs in some genera and immobilised in mature leaves in others, and the same protocol will therefore yield different outcomes across hosts for reasons that have nothing to do with delivery.

Calcium is more restrictive still. Calcium moves almost exclusively in the transpiration stream and is not appreciably retranslocated, so its accumulation in an organ depends on that organ's own xylem supply. Work on bitter pit in apple has shown that the calcium concentration of the fruit is related to the functionality of the fruit's xylem connection, which declines during development (Miqueloto et al., 2014). Injecting calcium into the trunk therefore cannot be expected to raise fruit calcium once xylem functionality in the pedicel has declined, irrespective of how much calcium is delivered to the leaves. Potassium and calcium are also implicated in cambial function and wood formation, so that injected concentrations sufficient to alter tissue status may act on the stem itself as well as on the intended sink (Fromm, 2010).

Iron behaves differently again, and its behaviour explains why it is the element for which injection has the strongest evidence. Iron chlorosis on calcareous soils is not usually a problem of total iron in the plant but of iron availability and physiological activity within the leaf, a discrepancy long recognised as the iron chlorosis paradox (Morales et al., 1998). Delivering soluble ferrous iron directly into the transpiration stream bypasses both the soil chemistry that immobilises applied iron and the root reduction step, and it delivers the element in a form that can be used. The narrow applicability of this logic should be noted: it works because the constraint on iron is one of supply chemistry rather than of internal redistribution, and it does not generalise to elements whose limitation lies elsewhere. Nitrogen illustrates the contrast, since stem injection of labelled ammonium nitrate into mature Sitka spruce (*Picea sitchensis*) was developed as a method for tracing whole-tree nitrogen dynamics rather than as a fertilisation strategy (Nair et al., 2014).

Table 1 summarises these element-specific constraints and their consequences for injection practice. The table is organised by element rather than by study because the constraints are chemical and therefore transfer across hosts, whereas the agronomic outcomes reviewed in Section 5 do not. It is intended to be read as a set of prior expectations against which the empirical evidence can be tested, and it identifies where the mechanistic reasoning is firm and where it rests on inference from general plant nutrition rather than on injection-specific evidence.

Table 1. Element-specific chemical and physiological constraints on nutrient delivery by stem injection in woody plants

Element	Principal constraint on delivery or use	Redistribution after arrival	Consequence for stem injection	Supporting references
Iron (Fe)	Immobilised in calcareous and alkaline soils; deficiency reflects availability and physiological activity rather than total tissue content	Limited redistribution once chlorosis is established; supply must reach the affected leaf	Best-matched element, because injection removes the binding soil-chemistry constraint directly	Ahmadi et al. (2023); Morales et al. (1998); Fernández-Escobar et al. (1993)
Zinc (Zn)	Low availability at high soil pH; formulation strongly affects uptake rate from the injection port	Moderate; sufficient to raise leaf concentration above critical thresholds under favourable formulation	Feasible but formulation-dependent; chelated forms substantially slow uptake relative to nitrate	Whiley et al. (1991); Worley et al. (1980); Navrot & Banin (1982)
Manganese (Mn)	Availability restricted at high pH and in well-aerated alkaline soils	Not characterised for injected material in the retained literature	Effectively untested in isolation; reported only within multi-element injections	Shirini et al. (2026)
Boron (B)	Requirement is met continuously by mass flow rather than by a pulse; a bolus is poorly matched to demand	Species-dependent; phloem mobility requires complexation with sugar alcohols	Delivery demonstrated, sufficiency not; critical leaf concentration not reached under a twice-yearly schedule	Askew & Chittenden (1936); Hu et al. (1997); Whiley et al. (1991)
Calcium (Ca)	Moves only in the transpiration stream; organ accumulation depends on that organ's own xylem supply	Negligible retranslocation	Cannot be expected to raise fruit concentration once pedicel xylem functionality declines; leaf effects reported in palm	Miqueloto et al. (2014); Damankeshan et al. (2026)
Magnesium (Mg)	Macronutrient demand large relative to injectable quantity;	Phloem-mobile	Direct test of an injected formulation was ineffective; also	Worley & Littrell (1980); Damankeshan et al. (2026)

Element	Principal constraint on delivery or use	Redistribution after arrival	Consequence for stem injection	Supporting references
	antagonism with co-injected cations reported		depressed by zinc injection in one palm trial	
Potassium (K)	Macronutrient demand large relative to injectable quantity; implicated in cambial function at the stem	Phloem-mobile	No demonstration of agronomically relevant delivery; potential direct effect on the injected stem	Fromm (2010); Damankeshan et al. (2026)
Nitrogen (N)	Annual requirement far exceeds injectable quantity for a mature tree	Highly mobile	Validated as a whole-tree tracer method, not as a fertilisation route	Nair et al. (2014)
Phosphorus and phosphite	Injected phosphite acts as an antifungal agent and is not equivalent to a plant-available phosphate source	Phosphite is mobile but not readily oxidised to phosphate in planta	Reports of injected phosphite improving tree condition do not constitute evidence for phosphorus nutrition	Dal Maso et al. (2017); Whiley et al. (1991)

Note. Constraints listed under 'principal constraint' combine soil-chemical and in-plant limitations because both bear on whether injection offers an advantage over conventional application. Entries in the final two columns are inferences from the cited evidence rather than direct experimental comparisons except where the reference reports an injection trial for that element. No entry should be read as an exhaustive account of the element's plant nutrition

4. Delivery Technology and the Problem of Dose Control

If the transport constraints described above set the outer limit of what stem injection can achieve, delivery technology determines how close a given application comes to that limit. The technology question is more consequential for nutrients than for pesticides, because pesticide efficacy is governed by whether concentration at the feeding site exceeds a toxicological threshold, whereas nutrient efficacy is governed by whether the total delivered quantity is large enough relative to canopy demand and is distributed to the deficient tissue. Dose control and distribution uniformity therefore move from secondary technical details to primary determinants of outcome.

4.1 Passive, Pressurised and Implantation Systems

Three families of approach have been used. Passive and low-pressure systems rely on the tree's own tension to draw solution from a reservoir, using a sealed capsule, a pressurised elastic tube or a spring-loaded injector to maintain contact and a modest positive pressure. A low-pressure apparatus developed for olive delivered solution at 60 to 80 kilopascals, described by its developers as below the level injurious to xylem, and was reported to be simple, safe and economical without requiring specialised equipment (Navarro et al., 1992). Pressurised systems drive solution into the stem at higher pressure, reducing application time at the cost of greater mechanical disturbance. Implantation places a solid or gel formulation in a drilled cavity and relies on gradual dissolution, an approach used for zinc in the form of capsules and of a zinc-bentonite preparation (Navrot & Banin, 1982; Worley et al., 1980).

The trade-off between speed and injury is the central design tension, and it has been quantified most clearly in citrus. Comparison of three injection techniques in huanglongbing-affected sweet orange (*Citrus sinensis*) found that low-pressure injection caused the least damage but was less effective at delivering the tested compounds than medium- or high-pressure injection, and that the compound producing the greatest external and internal damage at the injection site was nonetheless the one that improved tree health, reduced bacterial titres and increased yield (Archer & Albrecht, 2023a). That result is instructive precisely because it refuses a comfortable conclusion. Within this system, minimising injury and maximising delivery were opposing objectives, and the treatment that worked was the more damaging one. Whether the same trade-off holds for nutrient solutions has not been tested, but there is no obvious reason to expect it to disappear, and practitioners advised to prefer low-pressure systems on welfare grounds should understand that this preference may carry an efficacy cost.

Injection rate itself was characterised early for pressure systems in pecan (*Carya illinoinensis*), where the factors affecting the rate at which a tree accepts solution were identified as a practical constraint on field application (Worley & Littrell, 1981). The persistence of this constraint is evident in the conifer work described above, where uptake in resinous species was slow and sometimes incomplete and where injector geometry materially altered uptake rate (Sánchez-Zamora & Fernández-Escobar, 2004). Uptake rate is not a trivial logistical detail; a system that requires several hours per tree is not deployable across a commercial orchard, and abandonment of an incomplete injection leaves an unknown delivered dose.

4.2 Port Geometry, Number and the Uniformity Problem

Port design has been examined more thoroughly in the plant-protection literature than anywhere in the nutritional literature, and the findings are directly transferable to the question of whether a nutrient injection has treated the whole tree. The decisive finding is that spatial uniformity of an injected compound within an apple crown increased significantly with the number of ports and that four ports were required to achieve uniform distribution (Aćimović et al., 2014). Almost none of the nutrient trials reviewed in Section 5 report using four ports; several report one or two. If the apple finding generalises, a large proportion of the historical nutrient injection literature has been measuring the response of partially treated trees while reporting it as a whole-tree response.

Port creation method also matters. Comparison of drill-based and needle-based injection technologies with respect to the healing of injection ports on apple trees provided direct evidence that the two approaches differ in the wound they impose and in the rate at which that wound closes (Aćimović et al., 2016). Needle-based systems that avoid drilling reduce the volume of tissue removed, but they also constrain the deliverable volume and the depth reached, which returns the practitioner to the delivery-versus-injury trade-off from a different direction. Port angle, depth and sealing have each been shown to affect uptake in the older arboricultural literature, and the conifer study cited above showed that a larger-diameter, longer injector achieved the fastest uptake in resinous species while a smaller-diameter injector performed equivalently in non-resinous species with the added advantage of reducing wound size and healing time (Sánchez-Zamora & Fernández-Escobar, 2004).

Dose and timing interact with port design in ways that have been demonstrated for insecticides and assumed for nutrients. Insecticide dose and seasonal timing of trunk injection in apples were shown to influence both efficacy and the residues recovered in nectar and plant parts, establishing that the same injected quantity produces different tissue distributions depending on when in the season it is applied (Coslor et al., 2019). For nutrients this has a specific consequence that the literature has not addressed: the deficient tissue is usually new foliage, so the timing of injection relative to leaf expansion determines whether the delivered element reaches the sink that requires it or accumulates in mature leaves that have already been formed.

4.3 Automation, Standardisation and the Translation Gap

Recent engineering work has addressed the labour intensity that has historically restricted injection to high-value individual trees. An automated needle-based trunk injection system was developed and evaluated for huanglongbing-affected citrus, and a subsequent comparison of automated with manual injection systems for oxytetracycline delivery quantified the operational differences (Ojo et al., 2024). Analysis of the pathway from research to commercial deployment has identified the principal barriers as regulatory, formulation-related and economic rather than purely mechanical, and has noted that the development of injection hardware has outpaced the availability of active substances registered for this route (Toth et al., 2025).

That observation is doubly relevant to nutrition. On one hand, mineral nutrients are not subject to the same registration burden as pesticides in most jurisdictions, so the regulatory obstacle that constrains plant-protection injection is weaker for nutrient injection. On the other hand, the absence of a registration process also means that there has been no requirement to generate the dose-response, distribution and safety data that registration compels, and this is one plausible explanation for why the nutritional evidence base has remained methodologically weaker than the plant-protection evidence base despite being older. The comparative maturity of the two literatures is a consequence of regulatory asymmetry as much as of scientific interest.

Formulation chemistry remains the least developed element of the technology. Injected solutions must remain stable in the reservoir, must not precipitate on contact with xylem sap, and must not damage the tissue at the point of entry. The recommendation that ferrous sulphate be applied at 0.5 to 1 per cent to reduce the risk of foliar burning is the clearest published acknowledgement that concentration is bounded above by phytotoxicity as well as below by efficacy (Fernández-Escobar et al., 1993). Compatibility work in avocado (*Persea americana*) showed that formulation composition governs uptake time, since inclusion of zinc chelate substantially increased the time required for uptake compared with a formulation containing zinc nitrate (Whiley et al., 1991). The delivered dose is therefore not a free parameter but the outcome of a narrow window bounded by solubility, phytotoxicity, uptake rate and the tree's transpirational capacity on the day of application.

Table 2 compares the delivery approaches against the criteria that determine nutrient outcomes rather than against general convenience. The comparison shows that no single approach dominates: passive systems minimise injury but constrain dose and rate, pressurised systems deliver more but injure more, implants avoid the reservoir entirely but relinquish control over release rate, and automation addresses throughput without resolving any of the underlying delivery constraints.

5. Agronomic Evidence for Nutrient Correction by Stem Injection

The agronomic literature is examined here element by element, because the constraints identified in Section 3 predict that outcomes should differ systematically by element and because pooling across elements is the principal reason the field's overall efficacy has been overstated. Within each element the evidence is assessed for consistency, control adequacy, duration and the separability of the injected nutrient from co-injected compounds and from the wound itself.

Table 2. Comparison of stem-injection delivery approaches against criteria that govern nutrient outcomes

Approach	Operating principle	Reported strengths	Reported limitations	Supporting references
Passive and low-pressure devices	Solution drawn from a sealed reservoir by transpiration-generated tension, with modest positive pressure (of the order of 60 to 80 kilopascals)	Least injury at the port; simple, inexpensive and requiring no specialised equipment; suited to slow-uptake species where individual devices remain in place	Uptake governed by transpiration and therefore slow or incomplete in stressed trees, in early spring and in resinous species; delivered dose weakly controlled	Navarro et al. (1992); Sánchez-Zamora & Fernández-Escobar (2004); Archer & Albrecht (2023a)
Medium- and high-pressure injection	Solution driven into the xylem under externally applied pressure	Faster and more complete delivery of the intended dose; shorter application time per tree	Greater external and internal damage at the injection site; risk of tissue disruption increases with applied pressure	Archer & Albrecht (2023a); Worley & Littrell (1981)
Drill-based ports	Cavity drilled to a defined depth and angle to expose conductive xylem	Accommodates larger volumes and permits access to deeper xylem	Removes more tissue than needle-based entry; slower port closure	Aćimović et al. (2016); Sánchez-Zamora & Fernández-Escobar (2004)
Needle-based (drill-free) ports	Needle driven directly into the stem without removal of tissue	Smaller wound and faster healing	Constrains deliverable volume and depth reached	Aćimović et al. (2016)
Solid implants and capsules	Solid or gel formulation placed in a cavity and released by gradual dissolution	No reservoir to maintain; single operation; slow-release formulations tested for zinc	Release rate not controlled by the operator; delivered dose uncertain; no durable practice established	Worley et al. (1980); Navrot & Banin (1982); Neely (1973)
Automated and mechanised systems	Machine-positioned needle injection with programmed dose delivery	Addresses labour intensity and improves dose consistency between trees	Does not alter the underlying transport, uniformity or injury constraints; formulation and registration remain the binding barriers	Ojo et al. (2024); Toth et al. (2025)

Note. 'Reported strengths' and 'reported limitations' summarise findings from the cited studies, most of which evaluated non-nutrient solutes; transferability to concentrated inorganic nutrient solutions has not been tested directly and should be treated as provisional

5.1 Iron: The Strongest and Most Replicated Case

Iron is the element for which stem injection has the most convincing evidence, and the reasons are mechanistic as well as empirical. The earliest controlled work reported that injection of iron salts controlled lime-induced chlorosis in fruit trees (Wallace, 1935). Trunk implantation was shown to correct iron deficiency in pin oak (*Quercus palustris*) in the landscape context (Neely, 1973), and trunk injection of iron compounds was evaluated as a treatment for overcoming iron chlorosis in apple (Barney et al., 1985). Physiological rather than merely visual outcomes were addressed in a pair of studies reporting net photosynthesis and chlorophyll content in silver maple (*Acer saccharinum*) after trunk injection of ferrous sulphate, and net photosynthesis, chlorophyll and foliar iron in apple after injection with ferrous sulphate (Hurley et al., 1986a, 1986b). The progression from visual score to chlorophyll to gas exchange is important, because it moves the outcome measure from one that is susceptible to observer expectation toward one that is not.

The most informative single trial remains the comparison of iron compounds in chlorotic Manzanillo olive and Maycrest peach (*Prunus persica*), which used a low-pressure injector and a pressurised reservoir and applied treatments on several dates across two seasons. All treatments increased chlorophyll content relative to the control; ferrous sulphate was the most effective compound; its effect persisted for two seasons in peach and at least three in olive; it increased vegetative growth and affected cropping in the year following injection; and a concentration of 0.5 to 1 per cent was recommended to reduce the risk of foliar burning (Fernández-Escobar et al., 1993). Several features make this the strongest study in the corpus. It compared compounds rather than testing a single formulation against an untreated control, it followed trees for multiple seasons rather than a single season, it reported a persistence estimate, and it reported a dose ceiling set by injury. Its limitation is that it was conducted on severely chlorotic trees, where the scope for improvement is greatest and where a positive result is least surprising.

A more recent trial supports the same conclusion under a stronger comparative design. Eight-year-old peach trees on calcareous soil received soil application, foliar spraying or trunk injection of ferrous sulphate at four concentrations in a randomised complete block design over two years. Injection eliminated chlorosis by increasing chlorophyll and active iron in the leaves, and also increased fruit weight and volume, yield, and total soluble solids relative to the control, whereas soil and foliar treatments had no significant effect on fruit weight, volume or yield, and foliar application increased active leaf iron without significantly altering chlorophyll content (Zokaee Khosroshahi et al., 2023). The importance of this study lies in its inclusion of the two conventional alternatives within the same experiment. It is the clearest available demonstration that the advantage of injection is not merely that it works, but that it works where the alternatives, applied concurrently to comparable trees, do not.

Injection has also been used to generate the measurement it depends on. A chlorophyll meter was used to quantify the effectiveness of mid-summer trunk injection of iron on chlorotic pear (*Pyrus communis*) trees, which established a rapid non-destructive outcome measure appropriate to the time course of the response (Peryea & Kammereck, 1997). Applications outside the orchard are represented by a factorial study in an urban setting in which plane (*Platanus orientalis*) trees received trunk injection of iron, zinc and manganese in combination with soil fertilisation techniques, with morphological, biochemical, antioxidant and micronutrient outcomes measured in the leaves (Shirini et al., 2026). The factorial design of that study is a methodological advance on the older single-factor trials, because it permits the injection effect to be separated from the soil-amendment effect rather than confounded with it.

Confidence in the iron conclusion is therefore moderate to high for the specific claim that injected ferrous sulphate raises leaf chlorophyll and active iron in chlorotic trees on calcareous soils, and moderate for the claim that this translates into yield or growth benefit. The main residual reservations are that most trials used small numbers of trees, that untreated rather than wound-only controls predominate so the contribution of the wound itself is unquantified, that the trees selected were generally severely affected, and that the geographical concentration in Mediterranean and semi-arid calcareous environments limits generalisation to other soil types.

5.2 Zinc, Manganese and Boron: Partial Success and Documented Failure

Zinc has the second-largest literature and a much less consistent one. Trunk injection was compared directly with implantation of zinc capsules for the correction of zinc deficiency, providing an early head-to-head evaluation of the two delivery families for the same element (Worley et al., 1980). A different approach used trunk-implanted zinc-bentonite as a slow-release zinc source for apple, which addressed the release-rate problem that limits simple capsule implantation (Navrot & Banin, 1982). Neither line of work established a durable practice, and the subsequent development of zinc correction in pecan proceeded along a different route entirely, through soil banding, which was shown to correct zinc deficiency in that species (Wood, 2007). The displacement of injection by a soil method in the crop where pressure injection was pioneered is itself evidence about relative practicality, and it is not a favourable sign for injection.

The most analytically useful zinc and boron evidence comes from avocado, where phosphonate injected at three concentrations against Phytophthora root rot was used as a carrier for micronutrients. Formulations containing 17 per cent zinc chelate or 10 per cent zinc nitrate, injected twice in a growing season at 15 millilitres per metre of canopy diameter, raised leaf zinc above the critical concentration of 30 milligrams per kilogram of dry matter; inclusion of zinc chelate substantially increased uptake time relative to zinc nitrate; and formulations containing 0.9 per cent boron, injected on the same schedule, improved leaf boron concentrations but failed to reach the critical threshold of 50 milligrams per kilogram of dry matter (Whiley et al., 1991). This single study contains the field's clearest positive and clearest negative micronutrient results side by side, under identical conditions, and it demonstrates that the difference between success and failure lay in the element and its formulation rather than in the delivery method.

The boron failure is mechanistically coherent with Section 3.3. Boron's redistribution depends on the formation of complexes with sugar alcohols and is therefore species dependent (Hu et al., 1997), and the boron requirement of a crop is met continuously by mass flow in the transpiration stream rather than by a pulse. Delivering a bolus twice in a season is a poor match to that requirement. The earliest boron injection work is consistent: injection of borax solutions did alter the boron status of apple trees, which establishes delivery, but establishing delivery is not the same as establishing sufficiency (Askew & Chittenden, 1936). The distinction between demonstrating that an element enters the tree and demonstrating that enough of it enters to correct a deficiency runs through the whole of this literature and is very often elided.

Manganese evidence is sparse and is reported mainly as one component of multi-element injections rather than in isolation. The plane tree study cited above included manganese alongside iron and zinc but did not isolate the manganese effect (Shirini et al., 2026). Confidence for manganese is accordingly low, and the element should be regarded as untested by injection rather than as either supported or refuted.

5.3 Macronutrients and the Mass-balance Constraint

The most important negative result in this literature concerns magnesium. Neither foliar application nor pressure trunk injection of a magnesium-nitrogen formulation corrected magnesium deficiency in pecan (Worley & Littrell, 1980). This finding is rarely cited in contemporary discussions of injection, and its neglect is instructive, since it comes from the same research group and the same crop that produced the influential positive reports on pressure injection in the 1970s (Worley et al., 1976). A group that had every incentive to report success reported failure for a macronutrient, and the failure has a straightforward explanation.

The explanation is arithmetic. Injectable volumes are bounded by the rate at which a tree can accept solution and by the concentration at which the solution becomes phytotoxic, and the product of these two bounds is small relative to the annual requirement of a mature tree for magnesium, calcium, potassium or nitrogen. A micronutrient requirement is measured in grams per tree per year and can plausibly be met by a few hundred millilitres of a dilute salt solution; a macronutrient requirement is measured in hundreds of grams to kilograms and cannot. No published injection protocol resolves this arithmetic, and none of the macronutrient reports reviewed here presents a mass balance demonstrating that the delivered quantity is commensurate with demand.

This does not mean that macronutrient injection is never observed to produce effects. A trial in walnut combined systemic insecticides with a complete fertiliser applied by trunk injection against leopard moth in infested trees, reporting outcomes for the combined treatment (Mokhtaryan et al., 2021). The design of such studies, in which a fertiliser is co-injected with an active pesticide, makes the fertiliser contribution inseparable from the pest-control contribution and from the wound response, and they therefore cannot support a nutritional claim. Where phosphorus is concerned, the picture is further complicated because phosphite compounds are widely injected for their antifungal action, and an enhanced trunk injection formulation of potassium phosphite has been developed against chestnut ink disease (Dal Maso et al., 2017). Phosphite is not a plant-available phosphorus source in the way phosphate is, and reports of injected phosphite improving tree condition should not be read as evidence for phosphorus nutrition by injection.

Nitrogen occupies a different position again. Stem injection of labelled ammonium nitrate into mature Sitka spruce was developed as a tracer method for studying nitrogen dynamics at whole-tree scale rather than as a fertilisation technique (Nair et al., 2014). The distinction matters because the tracer application requires only that a detectable quantity enter and distribute, whereas fertilisation requires that an agronomically meaningful quantity do so. The existence of a validated tracer method is sometimes cited as though it demonstrated the feasibility of nitrogen fertilisation by injection, which it does not.

Confidence for macronutrient correction by stem injection is therefore low, and the single well-designed test available is negative. The appropriate conclusion is not that macronutrient injection is impossible in principle but that no study has yet demonstrated delivery of an agronomically relevant quantity, and that the one direct test of a macronutrient formulation found it ineffective.

5.4 Arborescent Monocotyledons and the Boundary of the Technique

Palms are treated separately for the anatomical reasons given in Section 3.2, and the evidence base is smaller but not negligible. The response of date palm (*Phoenix dactylifera*) to iron fertilisation was compared between trunk injection and soil application in an early study (Abo-Rady et al., 1987). A recent orchard trial on fifteen-year-old Mazafati date palms applied trunk injection of ferrous sulphate at three concentrations, root injection of ferrous sulphate, trunk injection of zinc aminochelate at two concentrations and trunk injection of calcium aminochelate at two concentrations, in a randomised complete block design with an untreated control and three replications. Trunk injection of iron at the highest concentration maximised flesh and seed weight; zinc injection produced the highest total fruit weight; iron injection significantly increased leaf iron, magnesium and calcium; and zinc injection raised leaf zinc and potassium while reducing iron and magnesium (Damankeshan et al., 2026).

The last of those findings deserves emphasis because it is the only clear report of antagonism following injection in the retained literature. Raising one element by injection depressed two others in the same leaf tissue, which is consistent with well-known cation interactions but which has almost never been examined in injection studies. Most trials measure only the injected element. If antagonism of this kind is general, the practice of measuring only the target element will have systematically concealed unintended nutritional consequences across the whole field. The reservation attaching to this specific study is that three replications is a small number for detecting the interaction effects the authors report, and the finding requires independent confirmation before it is treated as established.

The anatomical boundary of the technique is illuminated by work on a herbaceous relative. Injection of zinc sulphate into banana pseudostem was reported to triple the zinc content of the fruit and was proposed as an effective biofortification method (Mayorquín Guevara et al., 2021). The magnitude of that response, far larger than anything reported for a woody host, is consistent with the short transport distance, the absence of a lignified compartmentalising stem and the high sink strength of a rapidly developing bunch. It defines the upper bound of what stem-based delivery can achieve when anatomy is favourable, and by contrast it indicates how much of the modest response observed in woody hosts is attributable to the structure of the stem itself rather than to the delivery method.

Table 3 sets out the representative evidence by element and host, with the principal reported outcome and the main methodological limitation of each entry. The table is deliberately restricted to studies in which a nutrient was the injected substance or a separable component of the injected formulation; studies in which nutrients were co-injected inseparably with pesticides are excluded from it and are discussed only in the text.

6. Wounding, Compartmentalisation and the Physiological Cost of Repetition

Every injection is an injury, and the nutritional application differs from the plant-protection application in that a chronic deficiency implies indefinite repetition. The cost side of the ledger therefore carries more weight for nutrition than for a single-season pest intervention, yet it has been studied almost exclusively in the pest context.

6.1 Wound Geometry and the Compartmentalisation Response

The reassuring evidence comes from arboriculture. Wound responses of green ash (*Fraxinus pennsylvanica*) were examined for two years following trunk injection by sectioning trunks to look for infection associated with injection sites and by recording annual radial growth and closure rate. All healthy trees compartmentalised the injection wounds without signs of infection, decay or structural damage, and wound closure was positively correlated with tree health as measured by annual radial growth (Doccola et al., 2011). Two qualifications limit how far this can be extended. The trees were healthy, and the correlation between closure and radial growth means that the trees least able to close a wound are exactly those in poor condition, which again is the population most likely to be injected for a nutritional disorder. The observation period was two years, which is short relative to the productive life of an orchard tree receiving annual treatment.

Table 3. Representative evidence for nutrient delivery by stem injection, by element and host

Element and form injected	Host	Principal reported outcome	Main methodological limitation	Supporting references
Iron salts	Fruit trees (lime-induced chlorosis)	Chlorosis controlled by injection of iron salts	Early study; limited reporting of design and replication by contemporary standards	Wallace (1935)
Iron, trunk implantation	Pin oak (*Quercus palustris*)	Iron deficiency corrected in landscape trees	Landscape observation; no wound-only control reported	Neely (1973)
Iron compounds	Apple (*Malus domestica*)	Iron chlorosis overcome by trunk injection of iron compounds	Untreated rather than wound-only control	Barney et al. (1985)
Ferrous sulphate	Silver maple (*Acer saccharinum*); apple	Net photosynthesis, chlorophyll and foliar iron increased after injection	Small trials; single season reported	Hurley et al. (1986a, 1986b)
Ferrous sulphate and other iron compounds	Olive (*Olea europaea*); peach (*Prunus persica*)	All treatments raised chlorophyll; ferrous sulphate most effective; effect persisted two seasons in peach and at least three in olive; 0.5 to 1 per cent recommended to limit foliar burning	Severely chlorotic trees selected; no wound-only control	Fernández-Escobar et al. (1993)
Ferrous sulphate at four concentrations, with soil and foliar comparators	Peach	Chlorosis eliminated, chlorophyll and active iron raised, fruit weight, volume, yield and total soluble solids increased; soil and foliar treatments had no significant effect on fruit weight, volume or yield	Single site; two seasons; no wound-only control	Zokaee Khosroshahi et al. (2023)
Iron, mid-summer injection	Pear (*Pyrus communis*)	Chlorophyll meter used to quantify effectiveness of mid-summer injection on chlorotic trees	Outcome limited to a chlorophyll proxy	Peryea & Kammereck (1997)

Element and form injected	Host	Principal reported outcome	Main methodological limitation	Supporting references
Iron, zinc and manganese, factorial with soil fertilisation	Plane (*Platanus orientalis*)	Morphological, biochemical, antioxidant and leaf micronutrient responses reported	Element effects not separated; stress-responsive outcomes without a wound-only control	Shirini et al. (2026)
Zinc, injection compared with capsule implantation	Pecan (*Carya illinoinensis*)	Direct comparison of the two delivery families for zinc correction	No durable practice established; superseded by soil banding in the same crop	Worley et al. (1980); Wood (2007)
Zinc-bentonite implant	Apple	Trunk-implanted zinc-bentonite evaluated as a slow-release zinc source	Release rate not controlled; limited replication of the approach	Navrot & Banin (1982)
Zinc chelate or zinc nitrate, and boron, in phosphonate carrier	Avocado (*Persea americana*)	Leaf zinc raised above the critical concentration of 30 mg kg^{-1} dry matter; chelate substantially slower to take up than nitrate; leaf boron improved but did not reach the critical 50 mg kg^{-1} dry matter	Nutrients co-injected with an antifungal carrier applied for disease control	Whiley et al. (1991)
Borax solution	Apple	Boron status of trees altered by injection	Delivery demonstrated without assessment of sufficiency	Askew & Chittenden (1936)
Magnesium-nitrogen formulation	Pecan	Neither foliar application nor pressure trunk injection corrected magnesium deficiency	Single crop and formulation; negative result not subsequently retested	Worley & Littrell (1980)
Labelled ammonium nitrate	Sitka spruce (*Picea sitchensis*)	Stem injection validated as a whole-tree nitrogen tracer method	Developed as a tracer, not as a fertilisation route	Nair et al. (2014)
Ferrous sulphate; zinc aminochelate; calcium aminochelate	Date palm (*Phoenix dactylifera*)	Iron injection maximised flesh and seed weight and raised leaf iron, magnesium and calcium; zinc injection gave the highest total fruit weight and raised leaf zinc and	Three replications; antagonism finding requires independent confirmation	Damankeshan et al. (2026); Abo-Rady et al. (1987)

Element and form injected	Host	Principal reported outcome	Main methodological limitation	Supporting references
		potassium while reducing iron and magnesium		
Zinc sulphate, pseudostem injection	Banana (herbaceous boundary case)	Fruit zinc content tripled; proposed as an effective biofortification method	Not a woody host; included only to define the anatomical boundary of the technique	Mayorquín Guevara et al. (2021)

Note. mg kg⁻¹ = milligrams per kilogram. The table presents representative rather than exhaustive evidence; studies in which nutrients were co-injected inseparably with pesticides are excluded except where the nutrient contribution was separately measured, as in the avocado entry. 'Critical concentration' refers to the threshold reported in the cited source

Compartmentalisation capacity is also strongly genus dependent. Comparative assessment across cultivars of *Acer*, *Gleditsia* and other genera established that the ability to wall off a wound differs systematically among taxa (Santamour, 1984). A recent experimental study illustrates both the response and its limits. Internal necrosis was detected in stem cross-sections above the injection point in all examined honey locust (*Gleditsia triacanthos*) seedlings, with the proportion of necrotic tissue highest at the injection point and at one centimetre above it and declining markedly by three centimetres and further at five and seven centimetres; external lesions were visible in seventy per cent of treated seedlings; and in field-injected sessile oak (*Quercus petraea*) lesion length differed significantly between the upslope and downslope sides of the trunk under the higher injection volume (Paraschiv, 2026). The vertical confinement of necrosis is evidence of effective compartmentalisation, but the fact that necrosis occupied a substantial fraction of the cross-section at the port, and that lesion size varied with volume and with position on the stem, indicates that the injury is neither trivial nor uniformly distributed.

Port creation method modifies the injury. Drill-based and needle-based technologies differ in the healing of injection ports on apple trees, which establishes that the wound cost is partly a design variable rather than an unavoidable constant (Aćimović et al., 2016). Injector geometry likewise influences wound size and healing time, with a smaller-diameter injector reducing both while performing equivalently in non-resinous conifers (Sánchez-Zamora & Fernández-Escobar, 2004). These findings collectively support a conclusion that is more nuanced than either the reassuring or the alarmed position: the wound imposed by injection is real, is measurable, is compartmentalised effectively by healthy trees of species with good compartmentalisation capacity, scales with the volume and pressure applied, and can be reduced by design choices that generally also reduce delivery.

6.2 Injury Attributable to the Injected Substance

Separating the injury caused by the port from the injury caused by what passes through it requires a water-injected control, and such controls are rare. Where one has been used, the result was informative. Wound reaction to trunk injection of oxytetracycline was compared with injection of water in huanglongbing-affected sweet orange, and the comparison of these treatments with injection technique in a companion analysis showed that the substance injected, not only the port, contributed to the extent of external and internal damage, with oxytetracycline producing the greatest damage while also producing the health, titre and yield benefits (Archer & Albrecht, 2023a, 2023b). For nutrient injection this design is essential and almost entirely absent. Concentrated inorganic salt solutions have the chemical character most likely to injure living cells adjacent to the port, and the recommendation to restrict ferrous sulphate to 0.5 to 1 per cent to avoid foliar burning indicates that phytotoxic effects distal to the port also occur (Fernández-Escobar et al., 1993).

The absence of water-injected controls has a further analytical consequence that is seldom acknowledged. Wounding a stem provokes systemic responses, and a positive response to an injected nutrient measured against an untreated control conflates the nutrient effect with the wound effect. Where the outcome measured is a stress-responsive variable such as antioxidant enzyme activity, this conflation is not hypothetical. Studies reporting antioxidant and biochemical responses to micronutrient injection therefore require a wound-only control before the biochemical changes can be attributed to the nutrient (Shirini et al., 2026).

6.3 Cumulative Cost under Repeated Application

No retained study followed nutrient-injected trees through repeated annual treatment for long enough to quantify cumulative structural or physiological cost, and this is the single largest evidential gap in the field. The relevant considerations can be identified even though the data do not exist. Repeated ports must be placed in new positions to avoid injecting into previously compartmentalised and now non-conductive tissue, so the number of viable port positions is finite and declines over the treatment history of a tree. Compartmentalisation isolates the damaged tissue from the functional xylem, which by definition reduces the conductive cross-section available for subsequent injections and for normal water transport. The evidence that healthy trees close wounds faster implies a potential negative feedback in which a tree weakened by repeated injection closes subsequent wounds more slowly.

Persistence data provide the only indirect purchase on this question. Where an injected iron treatment persisted for two seasons in peach and at least three in olive, the required treatment frequency is correspondingly low and the cumulative wound load over a productive lifetime is bounded (Fernández-Escobar et al., 1993). This is a genuine and underappreciated argument in favour of iron injection specifically: the multi-season persistence changes the cost calculation qualitatively relative to a treatment requiring annual repetition. It does not extend to elements for which persistence has not been demonstrated, and for boron, where a twice-yearly schedule failed to reach the critical leaf concentration, the implied frequency is high and the cumulative cost correspondingly greater (Whiley et al., 1991).

Table 4 sets out the recurrent methodological limitations that constrain interpretation across this literature, with the way each limitation manifests and its consequence. The pattern it reveals is that the field's weaknesses are systematic rather than random: the same design deficiencies recur across decades and across research groups, which means that accumulating further studies of the current design will not resolve the outstanding questions.

7. Comparative Standing and the Decision Context

A delivery method is justified not by working but by working better than the available alternatives under specified conditions, at acceptable cost. This section places stem injection in that comparative frame.

Against soil application, injection has a decisive advantage in exactly one circumstance: when soil chemistry, rather than the quantity applied, is the binding constraint. On calcareous and alkaline soils this condition holds for iron and to a lesser degree for zinc and manganese, and the direct comparison in peach, in which soil and foliar treatments had no significant effect on fruit weight, volume or yield while injection did, is the clearest demonstration available (Zokaee Khosroshahi et al., 2023). Where the constraint is not soil chemistry, the advantage evaporates. Correction of zinc deficiency in pecan by soil banding shows that a soil method can succeed for a micronutrient when placement rather than chemistry is the problem, and it is materially cheaper and less invasive than injection (Wood, 2007). Similarly, work on macronutrient and micronutrient fertilisation rates in huanglongbing-affected sweet orange has addressed root growth, distribution and yield through conventional fertilisation, which remains the appropriate route where root function is retained (Kadyampakeni et al., 2023).

Table 4. Recurrent methodological limitations across the stem-injection nutrition literature and their consequences for interpretation

Limitation	How it appears in the evidence base	Consequence for interpretation	Supporting references
Absence of wound-only controls	Injected trees are compared with untreated trees; water-injected controls appear in the plant-protection literature but almost never in nutrient trials	Nutrient effect cannot be separated from wound effect; reported responses are upper bounds, and stress-responsive biochemical outcomes are uninterpretable	Archer & Albrecht (2023b); Shirini et al. (2026)
Unreported or insufficient port number	Most nutrient trials report one or two ports; the number required for uniform distribution has been determined only for a pesticide	Trees may be partially treated while the response is reported as a whole-tree response; leaf sampling without reference to port position may misrepresent treatment	Aćimović et al. (2014); Navarro et al. (1992)
Confounding by co-injected compounds	Nutrients are frequently carried in formulations applied primarily for disease or pest control, or combined with soil amendments	Attribution of the response to the nutrient is unsafe unless the nutrient effect is measured separately	Whiley et al. (1991); Mokhtaryan et al. (2021); Shirini et al. (2026)
Short observation periods	Most trials report one or two seasons; the longest wound-response study followed trees for two years on healthy specimens	Persistence and cumulative cost under repeated annual application cannot be assessed	Doccola et al. (2011); Fernández-Escobar et al. (1993)
Selection of severely affected trees	Iron trials are typically conducted on markedly chlorotic trees where scope for improvement is greatest	Effect sizes are not generalisable to mild or incipient deficiency, and a positive result is least informative in this population	Fernández-Escobar et al. (1993); Zokaee Khosroshahi et al. (2023)
Measurement of the injected element only	Full nutrient profiles are rarely reported, so antagonistic effects on non-target elements are not detected	Unintended nutritional consequences may be systematically concealed across the field	Damankeshan et al. (2026)

Limitation	**How it appears in the evidence base**	**Consequence for interpretation**	**Supporting references**
Heterogeneous outcome measures and dose units	Outcomes range from visual score to chlorophyll proxy to elemental analysis and yield; doses are expressed as concentration, mass per tree or volume per metre of canopy	Quantitative pooling is not possible and cross-study comparison of dose-response is precluded	Whiley et al. (1991); Zokaee Khosroshahi et al. (2023)
Taxonomic and geographical concentration	Evidence is dominated by deciduous fruit genera in Mediterranean and semi-arid calcareous systems; conifers and arborescent monocotyledons are sparsely represented	Generalisation beyond the sampled anatomy and environment is unsupported, and anatomical differences are known to alter uptake and distribution	Sánchez-Zamora & Fernández-Escobar (2004); Archer et al. (2022)
Low replication	Several influential findings rest on small numbers of trees, in one case three replications	Interaction effects and modest treatment differences are unlikely to be detected reliably	Damankeshan et al. (2026); Hurley et al. (1986a)

Note. Limitations are listed in approximate order of the extent to which they constrain the conclusions drawn in this review. The references identify studies in which the limitation is evident or, in the case of the first two rows, studies that demonstrate why the limitation matters; they are not offered as criticism of the cited work relative to the standards of its period

Against foliar application, injection has an advantage where the element in question is poorly mobile out of the treated leaf surface or where the deficiency is established and severe. Foliar iron application increased active leaf iron without significantly increasing chlorophyll content in the peach comparison, which is consistent with the known limitation on within-leaf iron mobility once chlorosis is established (Zokaee Khosroshahi et al., 2023). Injection also avoids drift, worker exposure and non-target effects, advantages emphasised throughout the plant-protection literature and equally applicable to nutrient sprays (Archer et al., 2022; Berger & Laurent, 2019; VanWoerkom et al., 2014). These advantages are real but they are not nutritional; they belong to the environmental and occupational domain and should be weighed there rather than being counted as evidence of agronomic superiority.

Cost and throughput remain the decisive practical constraints. Injection requires per-tree intervention with skilled labour, which restricts economic viability to high-value individual trees, to amenity and heritage specimens where replacement cost is high, and to intensive orchard systems where the alternative has demonstrably failed. Mechanisation reduces but does not remove this constraint, and the analysis of translation barriers indicates that hardware development has outpaced formulation and registration (Ojo et al., 2024; Toth et al., 2025). The extension of injection into agricultural production systems has been driven principally by pathosystems in which no alternative exists, and the technology has been carried into commercial use on that basis rather than on nutritional grounds (Hu et al., 2018; Li & Nangong, 2022; Vincent et al., 2022).

A wider point about the technology's trajectory should be registered. Trunk injection has been extended successfully to organic molecules, to essential oils and to nucleic acids, demonstrating that the route accommodates a chemically diverse range of solutes (Dalakouras et al., 2018; Werrie et al., 2021). This breadth is frequently cited as evidence of the method's general promise. It is more accurately read as evidence that the transport pathway is permissive for solutes with suitable physicochemical properties, which says nothing about whether the quantities required for nutrition can pass through it. The distinction between a route that can carry a signal and a route that can carry a load is the central conceptual issue in this field, and conflating the two is the most common error in the applied literature.

Table 5 states the conditions under which stem injection of nutrients is currently defensible, together with the strength of evidence supporting each condition. The exercise is intended to make explicit where practice can reasonably run ahead of complete evidence and where it cannot.

Table 5. Conditions under which stem injection of nutrients is currently defensible, with the strength of supporting evidence

Condition	Rationale	Strength of evidence	Supporting references
Soil chemistry rather than applied quantity is the binding constraint	Injection removes the soil-chemical barrier entirely; where that barrier is absent the advantage disappears	Strong for iron on calcareous and alkaline soils, supported by a trial including soil and foliar comparators	Zokaee Khosroshahi et al. (2023); Ahmadi et al. (2023); Morales et al. (1998)
The element is required in small absolute quantity	Deliverable quantity is bounded by uptake rate and by phytotoxicity, and is small relative to macronutrient demand	Strong as a negative constraint: the one direct macronutrient test was ineffective	Worley & Littrell (1980); Fernández-Escobar et al. (1993)
The deficiency is established and severe rather than incipient	Foliar application is less effective once chlorosis is established because within-leaf mobility is limited	Moderate; most trials selected severely affected trees, so performance in mild deficiency is untested	Zokaee Khosroshahi et al. (2023); Fernández-Escobar et al. (1993)
The host has adequate compartmentalisation capacity and is otherwise healthy	Wound closure is faster in healthy trees and compartmentalisation ability differs systematically among genera	Moderate; demonstrated over two years in one species and inferred for others from comparative compartmentalisation data	Doccola et al. (2011); Santamour (1984); Paraschiv (2026)
Sufficient ports are used to treat the whole crown	Distribution uniformity increases with port number; a single port treats only the sectors served by the injected xylem	Moderate for pesticides, untested for nutrients; the transfer to inorganic cations is an assumption	Aćimović et al. (2014); Holmes (1982); Navarro et al. (1992)
The treatment persists for more than one season	Multi-season persistence limits the cumulative wound load over the productive life of the tree	Moderate; reported for injected iron in two genera, not demonstrated for other elements	Fernández-Escobar et al. (1993)

Condition	Rationale	Strength of evidence	Supporting references
Tree value justifies per-tree intervention	Injection requires skilled per-tree labour; mechanisation reduces but does not remove this constraint	Strong as an economic constraint; supported by the deployment pattern of the technology	Ojo et al. (2024); Toth et al. (2025); Berger & Laurent (2019)
Conventional routes have been tried and have demonstrably failed	Soil methods can succeed for micronutrients where placement rather than chemistry is limiting, at lower cost and without injury	Strong; soil banding corrected zinc deficiency in the crop where pressure injection was pioneered	Wood (2007); Kadyampakeni et al. (2023)

Note. 'Strength of evidence' reflects the number of independent studies, the consistency of their findings and the adequacy of their controls, assessed against the criteria stated in Section 2.6. Conditions are cumulative rather than alternative: the case for injection is strongest where several hold simultaneously

8. Future Directions

The priorities below are ordered by the extent to which resolving them would change practice, and each is stated with the design that would resolve it rather than as an aspiration.

The first and most immediate priority is the introduction of wound-only controls into nutrient injection trials. At present the great majority of studies compare an injected tree with an untreated tree, which confounds the nutrient effect with the wound effect and makes every reported response an upper bound rather than an estimate. The remedy is inexpensive and requires no new technology: a water-injected treatment applied through the same port geometry, at the same pressure and on the same date. The relevant outcome measures are those most susceptible to confounding, namely stress-responsive biochemical variables, chlorophyll and growth, rather than tissue concentration of the injected element, which the wound cannot affect. Without this control the biochemical component of the current literature cannot be interpreted, and its introduction would immediately clarify a body of work that is otherwise uninterpretable (Shirini et al., 2026).

The second priority is the direct measurement of spatial distribution for injected nutrients rather than the assumption that it resembles the distribution of injected pesticides. The pesticide evidence establishes that uniformity depends on port number and that transport combines vertical and spiral movement with radial diffusion (Aćimović et al., 2014), but inorganic cations interact with cell wall exchange sites in ways that a moderately soluble organic molecule does not. The appropriate design is a stable-isotope or elemental mapping study in which an enriched or analytically distinguishable form of the injected element is quantified in a stratified sample of leaves whose position relative to each port is recorded, run at one, two and four ports in the same orchard and the same species. Existing methods for sampling xylem sap from adult trunks make it feasible to characterise the solute concentration profile in the transport pathway itself rather than only at the endpoint (Takamatsu et al., 2023). The result would determine whether the four-port recommendation derived from pesticide work applies to nutrients or whether cation retention requires a different and probably denser port arrangement.

The third priority is a mass-balance treatment of macronutrient delivery. The magnesium failure in pecan remains the only direct test of a macronutrient formulation and it was negative

(Worley & Littrell, 1980), but the reason for the failure has never been quantified. What is required is not another efficacy trial but a determination, for a defined host and age class, of the maximum quantity of a given element that can be introduced without phytotoxicity and within a workable application time, set against the measured annual requirement of that tree. This is a modest experimental undertaking with a decisive outcome: if the deliverable quantity is an order of magnitude below requirement, macronutrient injection can be set aside as a research direction, and the resources currently devoted to it redirected. If it is not, the failure requires a different explanation and the question reopens.

The fourth priority concerns duration and repetition, and it is the priority requiring the longest commitment. No study has followed nutrient-injected trees through the repeated annual treatment that a chronic deficiency implies. The design required is a multi-year trial in a commercial orchard in which trees receive injection annually for at least six years, with structured measurement of injection port closure, conductive cross-section retained, cumulative internal necrosis assessed non-destructively where possible and destructively in a sacrificial subset, alongside yield and leaf nutrient status. The two-year wound-response evidence available in green ash is encouraging but is too short and was obtained on healthy trees (Doccola et al., 2011), and the genus-dependence of compartmentalisation means such a trial must be conducted separately in species of contrasting compartmentalisation capacity (Santamour, 1984). The relevant policy implication concerns the advice given to growers and arborists, which currently rests on inference rather than on longitudinal data.

A fifth priority, of lower immediate consequence but considerable scientific interest, is the investigation of injection-induced ionic antagonism. The observation that zinc injection raised leaf zinc and potassium while reducing leaf iron and magnesium in date palm is the only such report in the retained literature and rests on three replications (Damankeshan et al., 2026). Confirmation requires a full nutrient profile rather than measurement of the injected element alone, applied across at least two hosts and two elements. If the effect proves general, it changes the risk profile of single-element injection materially, since correcting one deficiency by injection could induce another.

A sixth priority is formulation science, which has been almost entirely neglected relative to hardware. Uptake time was shown to depend substantially on whether zinc was supplied as a chelate or as a nitrate (Whiley et al., 1991), and the ceiling on ferrous sulphate concentration is set by phytotoxicity (Fernández-Escobar et al., 1993), yet no systematic programme has optimised injectable nutrient formulations against the joint criteria of solubility, stability in contact with xylem sap, uptake rate and tissue tolerance. Given that hardware development has outpaced the availability of suitable substances (Toth et al., 2025), formulation is the binding constraint on translation and warrants proportionate investment.

Finally, the geographical and taxonomic concentration of the evidence should be addressed deliberately rather than incidentally. Almost all iron injection evidence derives from Mediterranean and semi-arid calcareous systems and from a small set of deciduous fruit genera. Whether the same protocols perform comparably in humid subtropical and tropical orchard systems, in evergreen broadleaved species and in the arborescent monocotyledons is largely unknown, and the conifer evidence indicates that anatomical differences of this magnitude alter both uptake and distribution (Sánchez-Zamora & Fernández-Escobar, 2004). Immediate priorities among these are the first four; the remainder are longer-term but should be initiated in parallel, since the formulation and antagonism questions bear directly on the design of the longitudinal trial.

9. Conclusions

Stem injection delivers mineral nutrients into woody plants, and the fact of delivery is not in doubt. What this review set out to establish is whether delivery translates into agronomically meaningful correction of nutrient disorders, under what conditions, at what physiological cost, and with what degree of confidence. The answers differ sharply by element, and the field's principal error has been to generalise across elements from the one case where the evidence is strong.

The strongest conclusion concerns iron. Injection of dilute ferrous sulphate into the trunks of chlorotic trees growing on calcareous or alkaline soils raises leaf chlorophyll and physiologically active iron, and there is credible evidence that the effect persists for more than one season and that it can improve growth, yield and fruit quality where soil and foliar applications applied concurrently do not. This conclusion is supported by independent studies across several genera spanning nine decades, by physiological as well as visual outcome measures, and by at least one trial that included both conventional alternatives as internal comparators. It rests on a coherent mechanism, since the constraint on iron in these systems is the chemistry of supply rather than internal redistribution, and injection removes precisely that constraint. The reservations are that the trials are generally small, that severely affected trees predominate, that wound-only controls are almost absent so the wound contribution is unquantified, and that the environmental range sampled is narrow.

Conclusions for the other micronutrients are weaker and, in the case of boron, negative in an informative way. Zinc can be raised above critical leaf concentrations by injection under favourable formulation conditions, but the best evidence for this comes from a study in which zinc was carried in a phosphonate formulation applied for a different purpose, and the same study found that boron delivered on the same schedule failed to reach its critical threshold. That contrast is the most useful single result in the micronutrient literature because it holds delivery constant and varies only the element, demonstrating that success is governed by element chemistry and requirement pattern rather than by the delivery route. Manganese remains effectively untested in isolation. For macronutrients the evidence is negative or absent: the one direct test of a magnesium formulation found it ineffective, and no study has demonstrated the delivery of a quantity commensurate with the annual demand of a mature tree. The mass-balance constraint that explains this is arithmetic rather than biological, and it is unlikely to be overcome by improvements in hardware.

Regarding physiological cost, the balanced position is that injection imposes a real, measurable and locally substantial wound which healthy trees of species with adequate compartmentalisation capacity contain effectively, whose extent scales with volume and applied pressure, and which can be reduced by design choices that tend also to reduce delivery. The evidence that this cost remains acceptable under the repeated annual application a chronic deficiency implies does not exist, and its absence is the field's most consequential gap. Where a treatment persists across multiple seasons, as reported for injected iron, the cumulative burden is correspondingly limited and the cost calculation becomes considerably more favourable; where frequent repetition is required, it does not.

The broader significance of this synthesis lies in a distinction that the applied literature has repeatedly blurred. Demonstrating that a substance introduced into the xylem reaches the canopy establishes that the pathway is permissive; it does not establish that the pathway can carry the quantity a nutritional requirement demands, nor that the quantity arrives where it is needed rather than in the sectors of the crown that happen to be served by the injected xylem.

The transport pathway is a conduit for signals with considerable generality and a conduit for loads with severe limits. Recognising which of these two problems a given nutritional application presents is the single most useful principle available for deciding whether injection is worth attempting, and it explains almost the entire pattern of success and failure in the evidence reviewed here.

10. Limitations

This review is a narrative synthesis and carries the limitations intrinsic to that form. Study identification, selection and weighting involved judgement at every stage, and although the search strategy, eligibility criteria and appraisal criteria are stated explicitly, a different reviewer applying them would not necessarily retain an identical set of sources or assign identical weight to individual findings. Selection bias in favour of studies that address the review's organising questions, and interpretive bias in favour of the mechanistic framework adopted in Section 3, cannot be excluded despite the effort to represent negative and inconsistent findings prominently.

Coverage is a material limitation. Searching was confined to bibliographic resources accessible during preparation, and no subscription citation index was searched. The consequence is likely to be uneven rather than uniform, since older arboricultural, extension and regional horticultural reports are less consistently represented in the resources used than contemporary indexed articles, and the nutritional injection literature is disproportionately old. Assessment was restricted to publications available in English, which is a substantive constraint for a technique with a long history of investigation in Mediterranean Europe, the Middle East, South Asia and East Asia, and it is probable that relevant primary evidence in other languages has been missed. Some retained sources could be appraised only from bibliographic and abstract-level records rather than full text, and claims drawn from those sources were deliberately confined to what such records substantiate, which limits the depth of appraisal that could be applied to them.

The evidence base itself constrains what any synthesis can conclude. Outcome measures are heterogeneous, ranging from visual chlorosis scores to elemental analysis, gas exchange and yield, and doses are reported in incompatible units, so quantitative synthesis was not possible and no effect sizes are presented. Study designs are similarly heterogeneous, encompassing controlled orchard trials, greenhouse experiments, single-tree observations and tracer studies with quite different inferential capacities. Replication is generally low, several key findings rest on single studies with few replicates, and wound-only controls are almost entirely absent, so the contribution of the injection wound to reported responses cannot be separated from the contribution of the injected nutrient anywhere in this literature.

Geographical and taxonomic representation is uneven. Iron evidence derives overwhelmingly from calcareous and alkaline systems in Mediterranean and semi-arid environments and from a narrow set of deciduous fruit genera, and generalisation to humid tropical systems, to evergreen broadleaved species and to forest species is not supported. Long-term evidence is scarce throughout, and no study followed nutrient-injected trees through repeated annual treatment, so conclusions about cumulative cost rest on inference from short-term wound studies conducted for other purposes. Publication bias is a plausible additional concern in a field where a small number of research groups have produced a large share of the output and where negative results, of which one important example was recovered, are likely to be underrepresented relative to their frequency. Finally, injection hardware and formulation are developing quickly, and conclusions about technical feasibility drawn from the retained literature may date faster than conclusions about the underlying physiology.

Declaration of AI Use

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Competing Interests

Authors have declared that no competing interests exist.

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