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Review

The development and evolution of trunk injection mechanisms -a review

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ABSTRACT

Trunk injection of chemicals is an alternative to conventional methods of applying plant protection products, and it can potentially deliver the exact dosage of therapeutic material required by the plant without undermining environmental protection and human health. Although trunk injection has proven to be an effective method for managing systemic pathogens, several studies have highlighted limitations for large-scale commercial tree crop applications because of the manual process involved, emphasising the need for an automated injection system. The process of trunk injection involves the steps of hole creation on the main stem of a tree and the injectate delivery of the therapeutic material. Injection mechanisms can be categorised based on the approach of creating an injection port, method of injectate delivery, and pressure source used to apply the injected material. This review article extensively investigates the development of various trunk injection mechanisms, operating principles, and practical applications, critically presenting advances in tree injections and highlighting gaps in knowledge to guide the development of automated injection systems. This review also discusses optimum injection parameters, such as hole size, above-ground injection height, number of injection ports, injection rate, and pressure. Additionally, it covers other factors such as tree variability, leaks and backflow, and the question of air exclusion during injection and wounding that may contribute to the design of an effective injection device. Furthermore, recent advances in developing an automated injection device are highlighted.

1. Introduction

Landscape and orchard management relies on agrochemicals to manage tree pathogens, arthropod pests, excessive growth, and element deficiencies. Foliar and soil application of agrochemicals are the most common methods for landscape and orchard tree management (Berger & Laurent, 2019). Although agrochemicals can be quickly applied to multiple trees through sprayers, it is unsuitable for treating tall trees and is often accompanied by off-target and on-target losses due to various barriers for leaf uptake, degradation, and volatilisation of spray materials, thereby contaminating the environment and increasing pathogen resistance to agrochemicals (Berger & Laurent, 2019; Hu & Wang, 2016). As an alternative, soil application of agrochemicals can alter the soil ecosystem, hinder the delivery of applied agrochemicals (McCoy, 1976; Roach, 1939), and lead to groundwater pollution from leachate and accumulated residue. Thermotherapy has been introduced as a non-chemical method to treat pests and diseases (Ghatrehsamani et al., 2019a). However, field applications of thermotherapy are very challenging and costly because it requires covering individual plants (e.g., large trees) and increasing the temperature to a specific degree for a pre-determined time (Ghatrehsamani et al., 2019b, 2021). The shortcomings of external application methods of plant protective products have renewed interest in endotherapy via trunk injection.

Trunk injection of chemicals into trees is an attractive alternative because it can potentially deliver the exact amount of therapeutic material required by the plant into the vasculature without compromising environmental safety (Ferreira et al., 2023). In some instances, the most effective way to treat a specific pest or disease is via the intravascular application of a plant protective product, as is the case for diseases caused by phloem-limited bacteria, such as citrus greening (*Ca. Liberibacter asiaticus*) (Archer et al., 2022), pear decline (*Ca. Phytoplasma pyri*) (Blomquist & Kirkpatrick, 2002; Weintraub & Jones, 2010), lethal-yellowing of palm (*Ca. Phytoplasma palmae*) (Gurr et al., 2016), and almond leaf scorch (*Xylella fastidiosa*) (Amanifar et al., 2016) or

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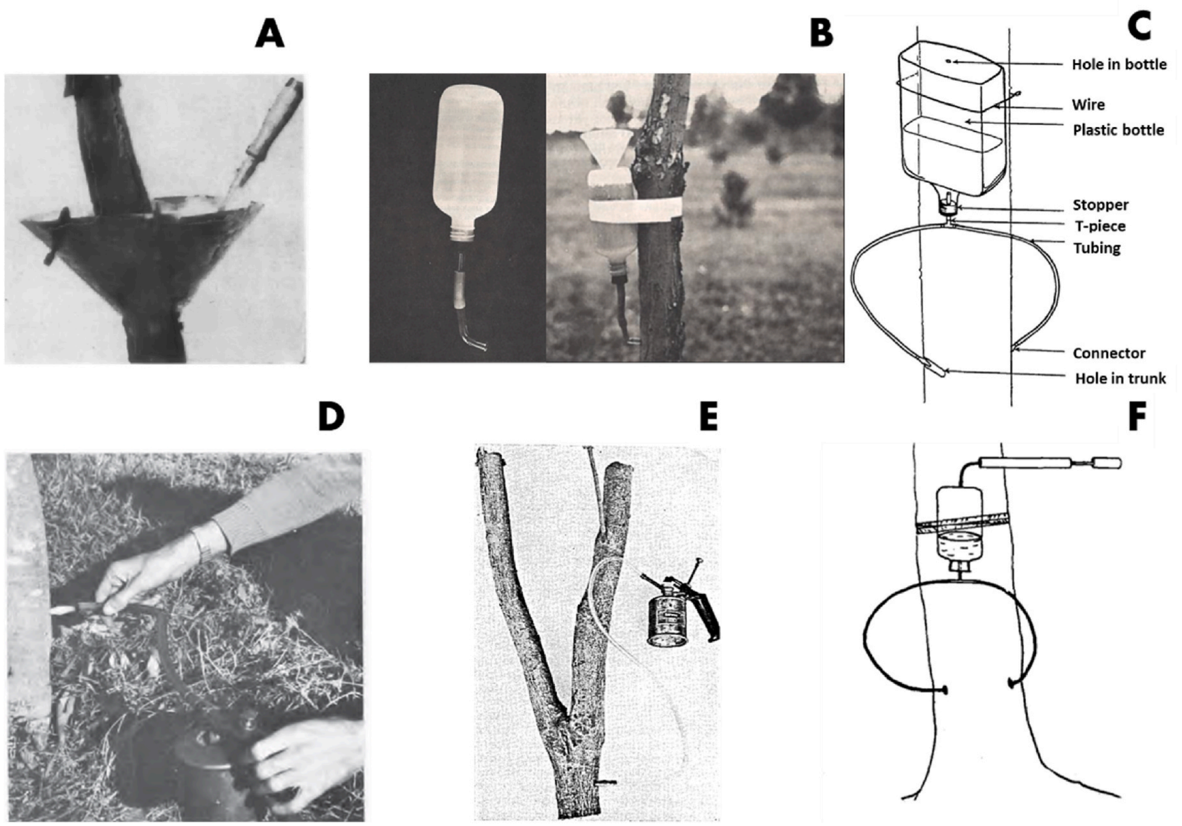

Fig. 1. **A.** Shevyrev's cone method showing the chisel used to make a cut underneath the solution (May, 1941). **B.** Injection device showing a modified medicine dropper attached to a plastic bottle and apparatus attached to a tree trunk (Schreiber, 1969). **C.** Schwarz & Van Vuuren (1971) injection device based on a modification to **1B** allowing for injection on both sides of the tree (Schwarz & Van Vuuren, 1971). **D.** Injection device showing modified blowlamp for pressurised injection (Schwarz et al., 1974). **E.** Blowtorch method (similar to **1D**) (Schwarz, 1974). **F.** Modification of the plastic bottle dispensing method with a bicycle pump (Schwarz, 1974).

insect borers that feed under the bark of trees. Foliar spray applications of some therapeutic materials cannot penetrate the tree in sufficient concentrations to effectively combat the pest or disease vector (Doccola et al., 2012). Moreover, in those instances, the level of resulting damage or tree death if effective treatment is not applied justifies the use of trunk injection (Al-Rimawi et al., 2019; Darrieutort & Lecomte, 2007; Doccola & Wild, 2012; Rumbold, 1920).

Trunk injection mechanisms can be categorised into drill-based and drill-free systems. Trunk injection may be distinguished from trunk infusion, given that with trunk infusion uptake of applied chemicals is dependent on atmospheric pressure and sap flow (Montecchio, 2013; Sachs et al., 1977; Sano et al., 2005), while trunk injection uses an external pressure source to force chemical materials into the stem (Brown, 1978; Sachs et al., 1977). In this study, trunk injection is categorised into pressurised and non-pressurised systems, referring to trunk infusion as a non-pressurised trunk injection method. Pressurised trunk injection mechanisms can be further classified based on pressure sources, including pumps, compressed gas, compression springs, elastomers, and hand pressure.

Recent review papers broadly categorise the different trunk injection technologies while elaborating on the physiology of trunk injection (Archer et al., 2022a; Berger & Laurent, 2019; Ferreira et al., 2023), discussing therapeutics applied (Archer et al., 2022b; Doccola & Wild, 2012; Ferreira et al., 2023) and emphasising the need for the development of a more efficient injection device suitable for large-scale applications (Archer et al., 2022a; Ferreira et al., 2023; Li & Nangong, 2022). The development of an automated injection system has also been emphasised and discussed by several other studies (Aćimović et al., 2014; Hu et al., 2018; Hu & Wang, 2016; Ojo et al., 2022). In response, this review article is written to guide the engineering of an efficient trunk injection device suitable for large-scale application by focusing in detail on existing designs of trunk injection mechanisms, their working principles and implementations, merits and drawbacks, and discussing optimum injection parameters, such as hole size, injection height, number of injection ports, injection rate, and pressure. Recent progress with an automated trunk injection device is also discussed.

2. The evolution of trunk injection technology

Trunk injection is the process of introducing chemical substances into the vascular system of a tree through a cut or a hole in the stem (Himelick, 1972; Roach, 1939). The evolution of trunk injection can be classified into three stages of development: the empirical period, low-pressure injection period, and high-pressure injection period.

2.1. Empirical period

The initial phase of trunk injection primarily involved empirical exploration without systematic scientific experimentation. Notwithstanding, the earliest records of trunk injection provided information including injection tool, hole depth, and injection height above the ground. The earliest record of injection was in 1158 (May, 1941); however, the earliest mention of a tool used in the process of trunk injection was in the writings of Leonardo da Vinci in 1894, detailing the application procedure and hole size for injecting a poisonous solution into a tree using a gimlet and a syringe. Da Vinci and other arborists from the 12th to 15th centuries suggested a hole depth to the pith of the stem (May, 1941; Roach, 1939). In 1765, a method of destroying insect

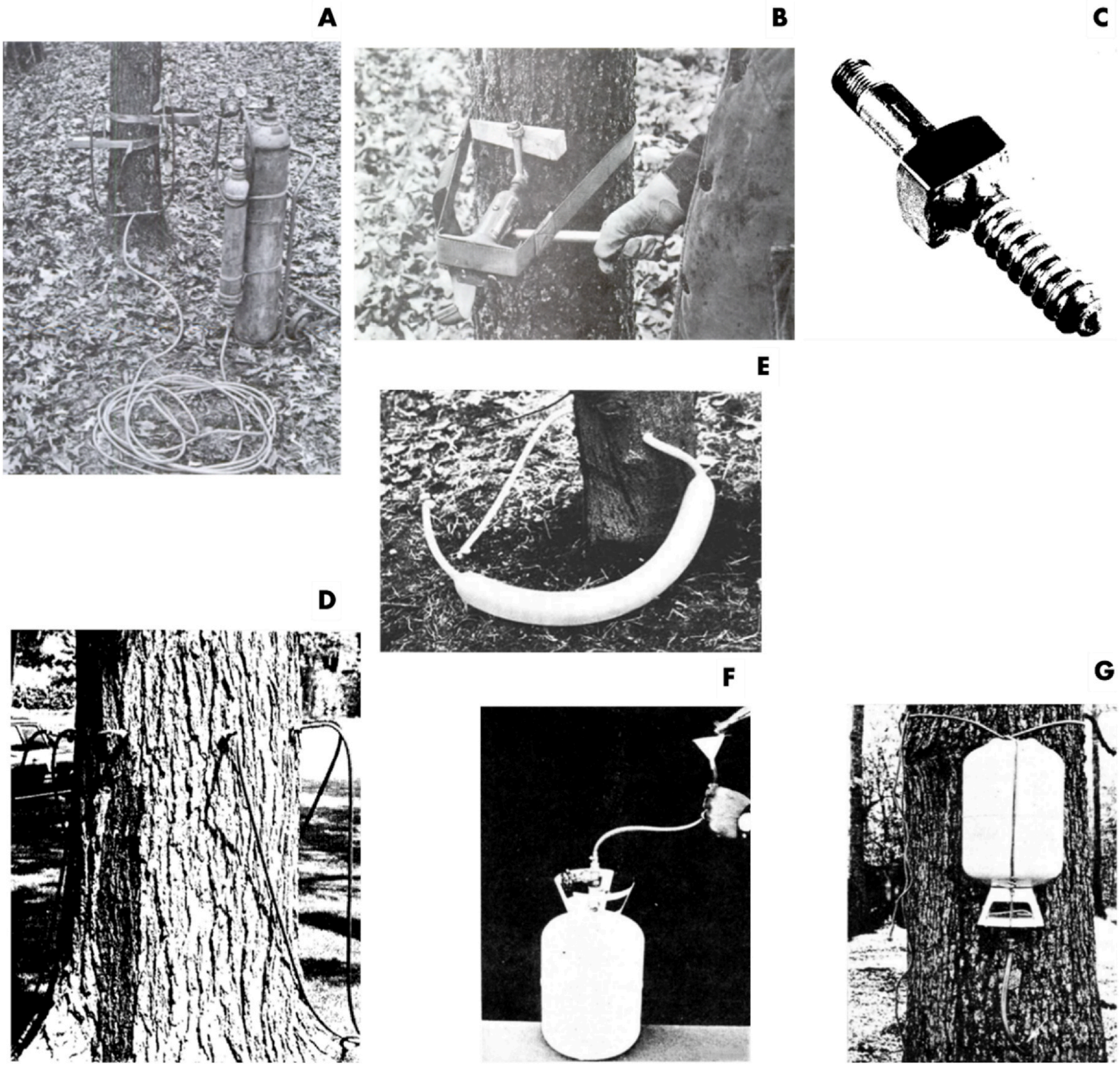

Fig. 2. **A.** Jones and Gregory's injection device (Jones & Gregory, 1971). **B.** Jones and Gregory's injector head firmly attached to a tree. **C.** Injector screw made from a 15.88 mm × 76.2 mm lag bolt with a 4.76 mm through hole (Himelick, 1972). **D.** Injection of elm tree via Heimelick's injection screw (Himelick, 1972). **E.** Pressure injection from latex tubing into apple trees (Pinkas et al., 1973). **F.** Filling the injection tank with the chemical solution before pressurising the tank (Filer, 1973). **G.** Injection via Filer's pressurised tank attached to a tree (Filer, 1973).

pests on trees and shrubs was devised that used an awl to cut a hole at an angle for injecting to a depth less than the pith (Wilson, 1847). Most early arborists created a single hole and plugged the hole with wood to complete the injection process (Roach, 1939), and an injection height not greater than 0.3 m above the root was recommended to inject honey into trees that bore sour fruit (Anonymous, 1596).

2.2. Low-pressure injection

This phase is mainly characterised by developing techniques for injecting trees stemming from scientific advancements across diverse fields during the 19th and 20th centuries. Understanding how compounds naturally move within trees led to the development of effective methods to introduce beneficial chemicals and ensure their targeted distribution within the tree's tissues. Shevyrev, in 1894, made use of waterproof cones that encircled the trunk and served as a receptacle for holding the chemical, such that a chisel was used to expose the wood tissue to the chemical beneath the liquid surface (May, 1941) (Fig. 1A), thereby excluding air from the injection process. Schreiber (1969) described existing methods as "inefficient or too laborious when large numbers of trees must be treated" and therefore devised the method of using a plastic bottle connected to a glass medicine dropper via a rubber hose to supply chemical solutions to a tree (Fig. 1B). By using a cork borer and a wood chisel, Schreiber (1969) ensured a watertight seal by using an injection port that was slightly smaller than the diameter of the flanged end of the medicine dropper. As an improvement to Schreiber's method, Schwarz & Van Vuuren (1971) used an apparatus (Fig. 1C) that allowed for two injection ports to be created on opposite sides of the tree. The ports were drilled at an angle and filled with tapered plastic reduction pieces that fitted the connectors at the end of the supply tubing. Air was excluded from the injection process by prefilling the injection ports and ensuring that the connecting hoses and plastic bottles were filled before attaching the hoses to the plastic reduction pieces. Most early techniques primarily involved the gravity-driven injection of solutions from elevated supply reservoirs (Himelick, 1972). Gravity flow methods require leaving the liquid container attached to the trunk for prolonged periods to supply a desired volume of injectate, which may cause chemical degradation and precipitates to begin to form thereby impeding liquid uptake (Himelick, 1972). Similar funnel-based procedures that encircle the tree trunk pose installation challenges for

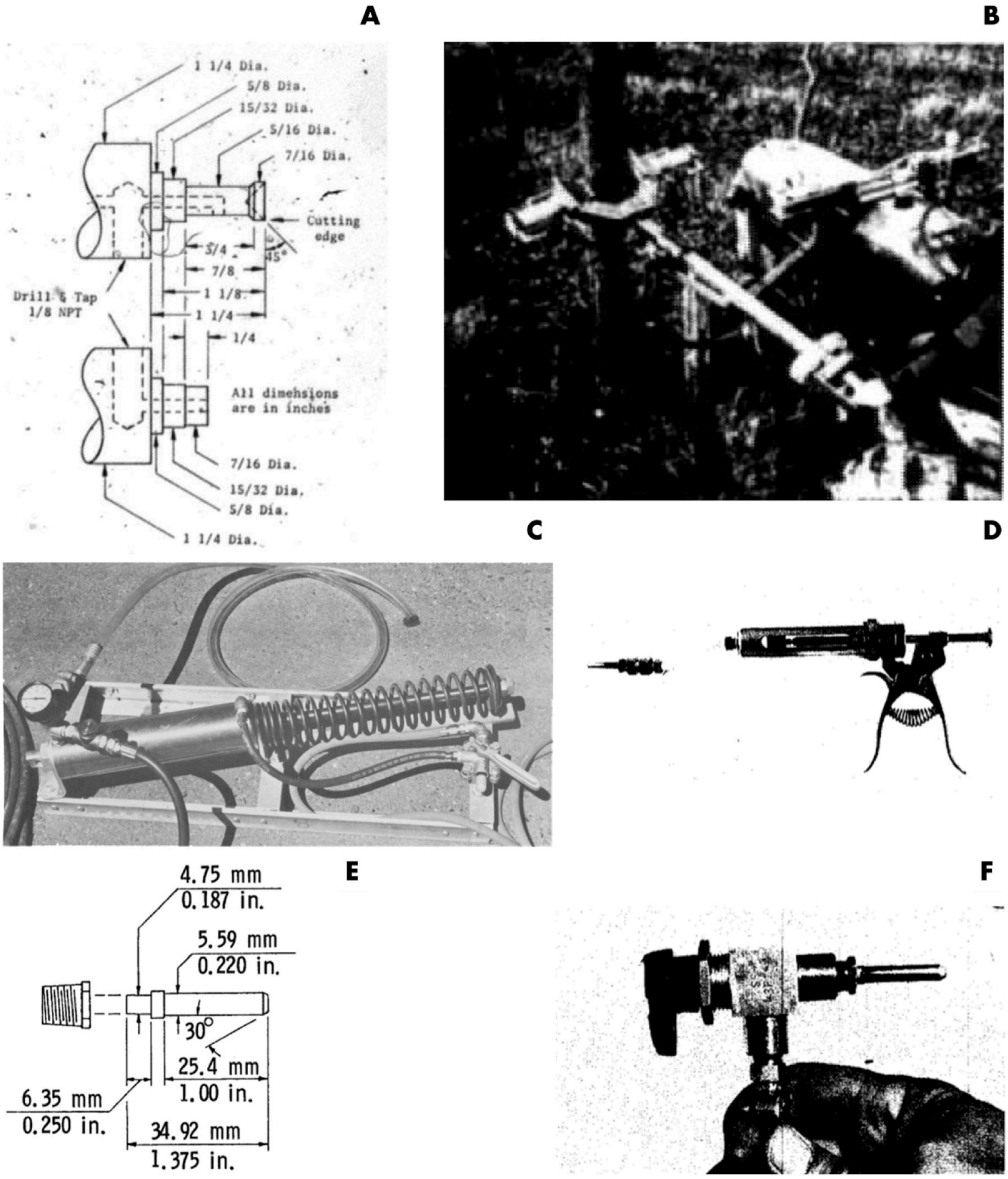

Fig. 3. **A.** Punch (top) and drilled hole (bottom) injectors (dimensions in the image are in inches) (Brown & Bachelor, 1974). **B.** Brown & Bachelor's injection apparatus mounted to the side of a tractor (Brown & Bachelor, 1974). **C.** Hydraulic cylinder, valves, and pressure gauge of Reil & Beutel's injection system (Reil & Beutel, 1976). **D.** Brown's modified pistol-grip veterinarian syringe injection device (Brown, 1978). **E.** Brown's stainless steel injector showing dimensions, inserted into a 3.175 mm hex pipe nipple (Brown, 1978). **F.** Injector and ball valve assembly (Brown, 1978).

achieving a perfect seal (Himelick, 1972).

A different setup (Fig. 1D), used in place of the plastic bottle by Schwarz & Van Vuuren (1971) and Schwarz et al. (1974), involved the use of a modified plumber's blowlamp (Fig. 1D and E) to inject the solution under air pressure enabled by the plunger of the blowlamp. Although this method documents the exclusion of air, there was no separation between the air pumped into the blowlamp and the injected solution, making air diffusion into the injected solution very likely. However, Schwarz & Van Vuuren (1971) successfully used this method to force 500 ml of tetracycline solution into mature citrus trees in 2 ½ hours. Schwarz (1974) improved his method by attaching a bicycle pump to the bottle (Fig. 1F), cautioning that the pressure applied should not be too high to avoid blowing the connector pieces out of the hole. The pressure applied by both methods was 0.138 MPa (Fig. 1E and F).

2.3. *High-pressure injection*

Jones and Gregory (1971) developed a high-pressure injection device with the unique feature of delivering chemical solutions to the outermost xylem tissues at a pressure of 0.66 MPa without leaks. The injection device consisted mainly of a pressure tank, injectate reservoir, and injector head (Fig. 2A and B).

Table 1
Categories of trunk injection devices based on method of hole creation and pressure source.

	Trunk injection devices					
	Hand pressure	Compressed gas	Compression spring	Elastomer	Pump pressure	Non-pressurised
Drill-Based		Schwarz et al. (1972) Filer, (1973) Reil and Beutel (1976)				
	Wilson et al. (1977)	Sachs et al. (1977)		Pinkas et al. (1973)	Himelick, (1972)	
	Sterrett and Creager (1977)	Brown, (1978)	Stallion 75 injector (Fuchs, 1988)	Navarro et al. (1992)	Sidewinder tree injector (Sidewinder Precision Tree Injectors, Longholme, QLD, Australia)	
	QUIK-jet (Arborjet Inc., Woburn, MA, USA)	Phair and Ellmore (1984)	ChemJet® Tree Injector (Chemjet Trading Pty. Ltd., Banyo, QLD, Australia)	Flexinject injector (T.J. Bio Tech LLC, Lakeland FL, USA)		Schreiber (1969)
	APM injector (Fuchs, 1988)	Helson et al. (2001)				Schwarz & Van Vuuren (1971)
		Arborchem (Fuchs, 1988) Systemic tree injection tubes (Helson et al., 2001) Quik-jet Air Injection System (Arborjet Inc., Woburn, MA, USA) Ecoject injection system (Lallemand, Ontario, Canada) TREE IV (Arborjet Inc., Woburn, MA, USA) Q-connect (Rainbow Ecoscience) Mauget microinjection device (Mauget, Arcadia, CA, USA) Tree Tech Micro Injection (Tree tech microinjection system, Morriston, FL, USA)				
Drill-Free	Wedgle ® Direct-Inject™ (ArborSystems, Omaha, NE, USA)	Jones & Gregory's (1971) Mayhead (1991)		Trecise™ (Invaio Sciences, Cambridge, MA, USA)	Ojo et al. (2024), Ojo et al. (2022)	BITE® Tool (Montecchio, 2013)

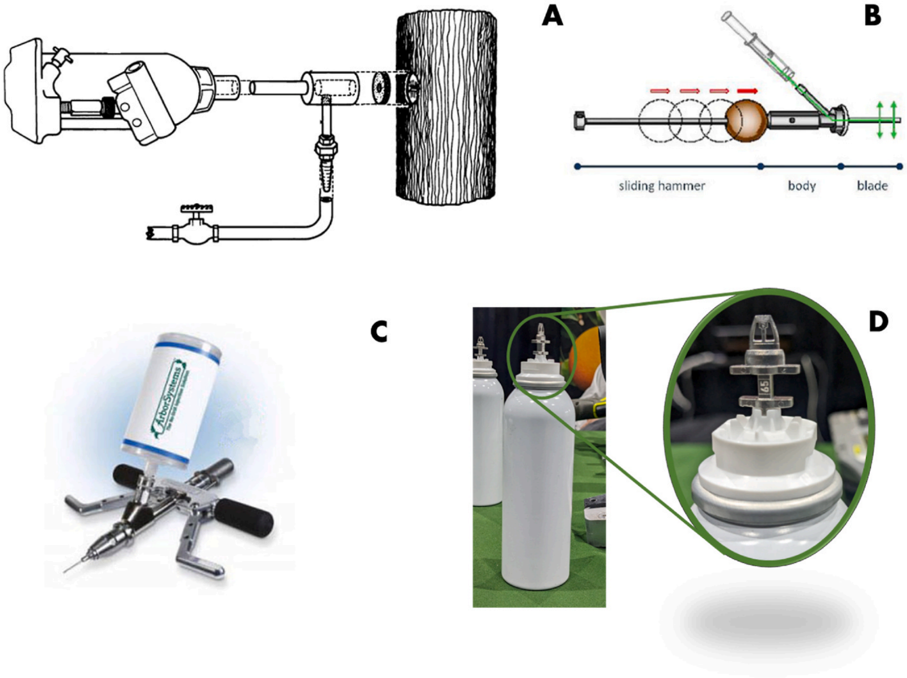

Fig. 4. **A.** Exploded view of Gregory's injection device (Jones & Gregory, 1971) **B.** University of Padova's BITE® Tool (Montecchio, 2013). **C.** Wedgle ® Direct-Inject™ (ArborSystems, Omaha, NE, USA) Note: From Wedgle Direct-Inject by ArborSystems, 2017 (https://www.arborsystems.com/find-a-product/injection-systems-2/wedgle/) Copyright 2017 by ArborSystems, Inc. **D.** Trecise™ injection canister showing exploded view of the attached injection blade (Invaio Sciences, Cambridge, MA, USA).

One of the most significant advancements in the technology of injection was the development of the injection screw (Fig. 2C). Himelick (1972) used a hollow threaded lag bolt for gripping the bark and wood tissue during injection, enabling an increase in injection pressure threshold to over 2.6 MPa without leaks or injector blowout. Although Himelick's method (Fig. 2C and D) allowed for large volumes of solution to be injected within a short period (over 75.7 L in 20–30 min), it was not ideal as it involved connecting a compressed gas tank directly to the reservoir of the chemical solution, which may cause the compressed gas to diffuse or react with the injected solution.

Probably unaware of Himelick's work, Pinkas et al. (1973) endeavored to overcome the shortcomings of Schreiber, Schwarz & Van Vuuren's designs by developing a pressurised injection device for injecting apple trees (*Malus sylvestris* Mill.) at a starting pressure of 0.14 MPa using a surgical latex tubing (Fig. 2 E). Filer (1973) developed an injection device with the motivation that it would be low-cost, lightweight, and fast-acting. The injection device consisted mainly of a pressure tank and connector fittings (Fig. 2F and G), delivering the injected solution at a pressure of 0.45 MPa. Similar to Himelick's design, Filer's apparatus held compressed air and the chemical solution in the same tank, which may lead to the air diffusing in the injected solution and cause air embolism in the plant.

Brown and Bachelor, (1974) began preliminary research on designing a portable, easy-to-use injection device that could be used for multiple tree injection of growth regulators along powerline rights-of-way, stating that previous mechanisms did not permit the rapid and continuous treatment of trees. While applying pressures up to 2.78 MPa, Brown and Bachelor, (1974) experimented with two injectors, punch and drilled-hole injectors (Fig. 3A), and found that the punch injector that was forced radially into the tree trunk by a hydraulic cylinder had a lower injection rate compared to the drilled-hole injector that was force-fitted into a radially drilled hole. The apparatus consisted of a U-shaped clamp attached to a positioning arm to hold the injectors. The entire apparatus was mounted on the side of a tractor (Fig. 3B).

Modifications made by Reil & Beutel (1976) to Himelick's works popularised the lag screw injection method, and their modified setup was the most widely used method for experimental purposes (Navarro et al., 1992). It consisted of a hydraulic cylinder (Fig. 3C) that converted gas pressure to solution pressure thereby eliminating direct contact between the compressed gas and injected solution.

Following the preliminary work of Brown and Bachelor, (1974), Brown (1978) developed two prototype injection devices. The first was a modified pistol-grip veterinarian syringe injection device (Fig. 3D), which was portable and similar to devices used in other studies (Sterrett & Creager, 1977; Wilson et al., 1977) but too slow for the control of regrowth along power lines though the device applied pressure of 0.69 MPa (Brown, 1978). The second was a less portable, but much faster, system that consisted of an injector and ball valve assembly (Fig. 3E&F), a battery-powered drill, an injection cylinder, and a portable air tank that was successfully utilised to inject trees using pressures as high as 1.38 MPa without bark blowouts, injector leakage, or injector blowouts.

3. Classification of trunk injection

Trunk injection involves the steps of hole creation and injectate delivery such that injection mechanisms can be categorised based on the approach of hole creation, method of injectate delivery, and pressure source used to supply the injected material. The trunk injection mechanisms described are those used for therapeutic purposes and can be categorised as drill-free or drill-based methods, and further subdivided into pressurised or non-pressurised systems.

3.1. Method of hole creation

3.1.1. Drill-based

Drill-based injection methods use a drill to create the injection port before applying the therapeutic material, either using a nozzle, a needle, or an injection screw. Drill-based methods provide various options for hole depth and diameter due to the availability of different drill bit sizes and are the most common methods of trunk injection (Table 1) (Berger

& Laurent, 2019; Li & Nangong, 2022).

Experiments conducted by Sachs et al. (1977) using three drill bits (auger, twist, and Jobber's bits) at different speeds (550, 1150, and 1720 rpm) showed that the type of drill bit and drill speed influenced the injection rate, indicating that the quality of the drilled hole affects the delivery rate of injected compounds. Wilson et al. (1977) observed that the best results from their experiment were achieved by inserting and withdrawing the rotating bit multiple times to remove all shavings from the hole. Sachs et al. (1977) concluded that the drilling of injection ports should be performed at high speeds to minimise the tearing and compression of the conducting vessels by the cutting action. Similarly, Reil (1979) recommended that holes be cleaned by moving the bits in and out of the hole using sharp drill bits rather than dull bits that seal the tissues and hinder fluid movement into the xylem.

The location of the injection port is vital because liquids flow faster in the newly formed xylem beneath the bark, slowing down as depth increases (Reil, 1979; Reil & Beutel, 1976). Brown (1978) drilled three holes at a 45-degree angle into the trunk to ensure that the applied growth regulator was injected only into the outer rings of the sapwood. The injection system was employed to inject over 400 trees, including silver maple *(Acer saccharinum)*, red oak *(Quercus rubra)*, American sycamore *(Platanus occidentalis)*, American elm *(Ulmus americana)*, and Siberian elm (*Ulmus pumila)*, with trunk diameters ranging from 0.1 to 0.4 m.

Similarly, Wilson et al. (1977) ensured that drilled holes were exclusively located within the sapwood by drilling holes tangentially to the stem of American elm trees, 101.6–152.4 mm diameter at breast height (DBH). Slanted holes of Himelick's (1972) injection screw method tended to cause blowouts. Therefore, all holes were drilled horizontally towards the centre of the tree. The much higher pressure used by Himelick (1972) compared to Brown (1978) and Wilson et al. (1977) could have contributed to the blowouts. Additional injection devices that require drilling are listed in Table 1.

3.1.2. *Drill free*

Drill-free injection methods eliminate the need for drilling by forcing a needle, blade, or injector into the stem. Jones & Gregory's (1971) drill-free injection apparatus was designed to enable the pressurised injection of solutions directly into the outermost xylem tissues. Components of the device can be found in Fig. 4A. Trunk injection was performed by creating a circular opening using a bow punch, approximately 34.9 mm in diameter, to penetrate the bark of the targeted tree. A wedge-shaped hole is carefully created at the centre of the exposed sapwood using a 12.7 mm chisel with a hole depth reaching two or three annual rings. Subsequently, a neoprene gasket is inserted into the hole within the bark. An injector head, coupled with a hydraulic jack, is then positioned, with the belt supporting the base of the jack and securely fastened around the tree (Fig. 2B). The injector head is pressed firmly against the gasket by operating a jack to establish a tight seal. The solution is dispensed without any leakage from the tree by opening a flow valve and applying pressures of up to 0.66 MPa.

The University of Padova, Italy, developed a manually operated injection mechanism (BITE® Tool) consisting of a sliding hammer for axial insertion and removal of the needle, a latex gasket that presses against the tree to form a seal, a connector to the solution container, and replaceable blades of varying lengths (Fig. 4B). Although injection is non-pressurised, Montecchio (2013) mentioned that the lenticular, biconvex shape of the blade enhances passive uptake by the venturi effect. The device also has the unique feature of minimal disturbance to the wood tissue, promoting quicker wound healing. The blades separate the wood fibres, enabling access to the inner xylem vessels with minimal friction. Once the blade is removed, the plant tissue is reported to partially return to its original state due to its elasticity and turgidity, and the healing process is completed in just a few weeks (Montecchio, 2013).

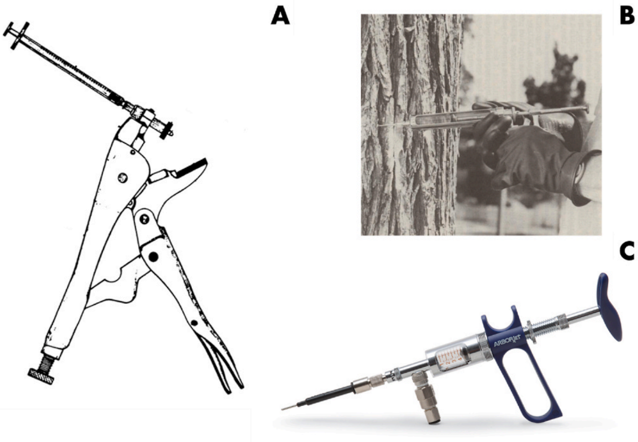

Fig. 5. A. Sterrett & Creager's injection device (Sterrett & Creager, 1977). **B.** Wilson's injection device (Wilson et al., 1977) **C.** QUIK-jet ® injection device (Arborjet Inc., Woburn, MA, USA). Note: From QUIK-jet Kit by Arborjet, 2022 (https://arborjet.com/product/quik-jet-kit/) Copyright 2022 by Arborjet, Inc.

The Wedgle® Direct-Inject™ is a drill-free mechanism by ArborSystems (Omaha, NE, USA) that consists of an injection tool with two handles attached to a spring-loaded piston for forcing solution into the tree by hand pressure. An injection pouch or bottle containing the chemical solution is attached to the device, and injection tips serve as solution outlets (Fig. 4C). The mechanism features quick-connect fittings for the injection tips and injection pouch. Like Montecchio's injection device, the Wedgle® Direct-Inject™ uses a tip setter (sliding hammer) to set and remove the injection tips. Unlike the BITE® Tool (Montecchio, 2013), the injection tip has a circular cross-section with a wedge-shaped or pointed tip, and a plug is inserted into the tree using a wedgeCheck punch (Arborjet Inc., Woburn, MA, USA) to keep the injected solution from leaking out during injection. Hand pressure hastens the injection process, but like the previously discussed mechanisms, it cannot be used for simultaneous injection at multiple ports.

A recent device, Trecise™ injection (Invaio Sciences, Cambridge, MA, USA) (Fig. 4D), uniquely features a minimally invasive design whereby a blade with a maximum thickness of 3.2 mm and depth of penetration of 9.5 mm delivers the therapeutic solution under pressure, allowing an application to small trees (10–150 mm stem diameter). Although the device enables closed chemical application when the blade is inserted into the stem with a setting device, the injected dosage is fixed, and the canisters are not reusable.

3.2. *Method of injectate application*

3.2.1. *Pressurised injection*

Pressurised injection provides a significant advantage when injection speed is crucial, rapid distribution throughout the root system is desired, and especially for dormant deciduous trees (Sachs et al., 1977). With methods that rely on external pressure, delivery times can be predicted even in suboptimal conditions, allowing for the easy planning of the number of plants to be treated per day (Montecchio, 2013). Pressure injection reduces labour for completing tree treatment (Himelick, 1972) and is more suitable for antibiotics that deteriorate over time, such as tetracyclines (Schwarz, 1974). A pressure source, including hand pressure, compressed gas, compression spring, elastomer, and pump pressure, provides the necessary force to inject desired therapeutic materials into the stem.

3.2.1.1. Hand pressure. Sterrett & Creager (1977) modified vice grip locking pliers to inject seedlings and small branches ranging from 6 to 36 mm in diameter. The tapered tip of the injector is inserted into a predrilled hole and secured in position by closing the Vise-Grip locking pliers (Fig. 5A). A prefilled syringe is then inserted into the injection

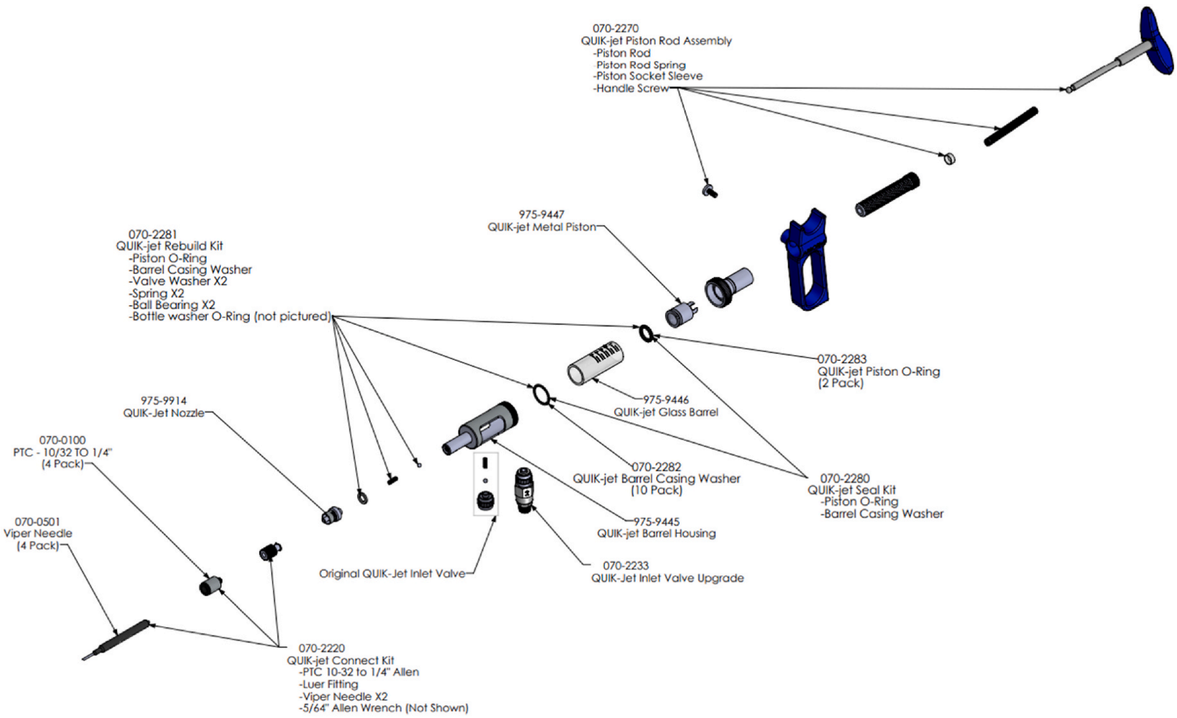

Fig. 6. Exploded view of Quik-jet injection system (Arborjet Inc, Woburn, MA, USA). Note: From QUIK-jet Kit by Arborjet, 2022 (https://arborjet.wpenginepowered.com/wp-content/uploads/2018/05/Quik-Jet-Customer-Drawing-2-1.pdf) Copyright 2022 by Arborjet, Inc.

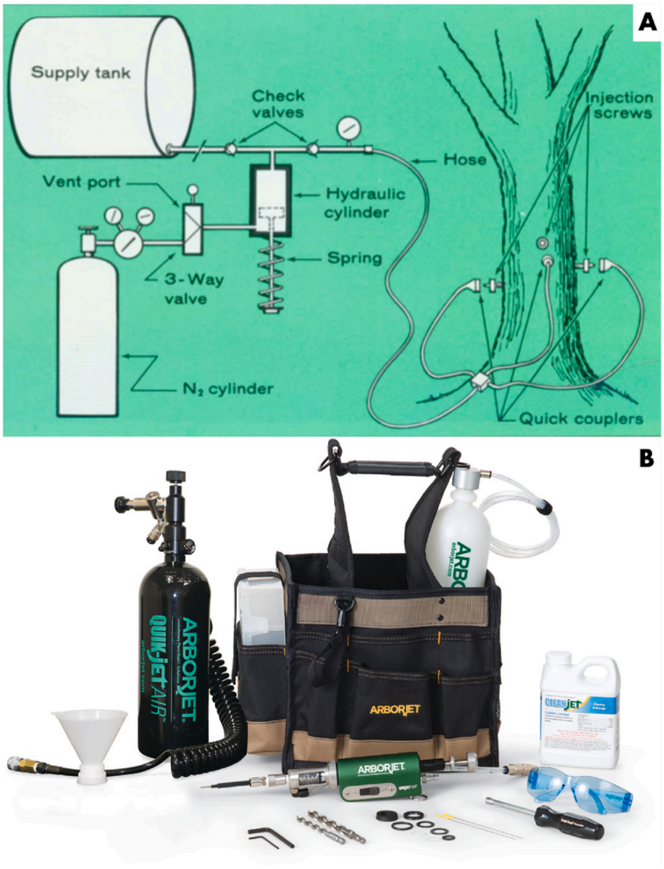

Fig. 7. **A.** Reil's injection system (Reil, 1979) **B.** Quik-jet AIR injection system (Arborjet Inc, Woburn, MA, USA) Note: From QUIK-jet AIR Kit by Arborjet, 2022 (https://arborjet.com/product/quik-jet-air-kit/) Copyright 2022 by Arborjet, Inc.

apparatus and used to force the solution into the tree by hand. A polypropylene syringe, 4.4 mm in diameter, enables manual application of pressure up to 2.35 MPa (Sterrett & Creager, 1977).

Wilson et al. (1977) forced chemical solutions into drilled holes by hand pressure on a syringe with an injection device that consisted of a 50-ml pistol-grip syringe and a 12-gauge needle (Fig. 5B). Compared to Sterrett & Creager's (1977) injection device, the syringe featured a threaded plunger with a hex nut handle, probably used to adjust the volume of injected solution, and the device was used on mature trees (101.6 mm–152.4 mm DBH).

The QUIK-jet® (Arborjet Inc., Woburn, MA, USA) is similar to Wilson's injection device but features a spring-loaded piston that enables the self-refilling of the glass barrel containing the injected solution (Fig. 5C). It also allows for adjustable injection dosage by loosening the stop nut and adjusting the threaded piston sleeve to supply a precise volume from 1 to 5 ml at a time. Its additional components can be seen in Fig. 6. However, the design of the injection needle requires that the mechanism be used with Arborplugs (Arborjet Inc., Woburn, MA, USA), which remain in the wood tissue after injection and have been reported to preclude the healing of the injection port (Archer & Albrecht, 2023; Aćimović et al., 2016; Hauer et al., 2022).

3.2.1.2. *Compressed gas.*

Reil & Beutel's (1976) injection device consists mainly of injector screws, a 946.4 ml two-way hydraulic cylinder, a liquid storage tank, and a compressed gas cylinder. The connection of the parts and other components of the device is shown in Fig. 7A. A unique feature of Reil & Beutel's (1976) injection device is the use of a shock-absorber coil booster spring attached to the piston of the hydraulic cylinder between the bottom of the cylinder and the end of the shaft permitting the automatic recharge of the system with the chemical solution after the gas pressure is released. Although this feature adds additional resistance to the extension stroke of the hydraulic cylinder, it eliminates gas depletion on the retraction stroke. An advantage of using compressed gas as a pressure source is that the injected solution can be rapidly delivered to multiple injection ports (Fig. 7A).

Compared to Reil & Beutel's (1976) injection device, Brown's (1978)

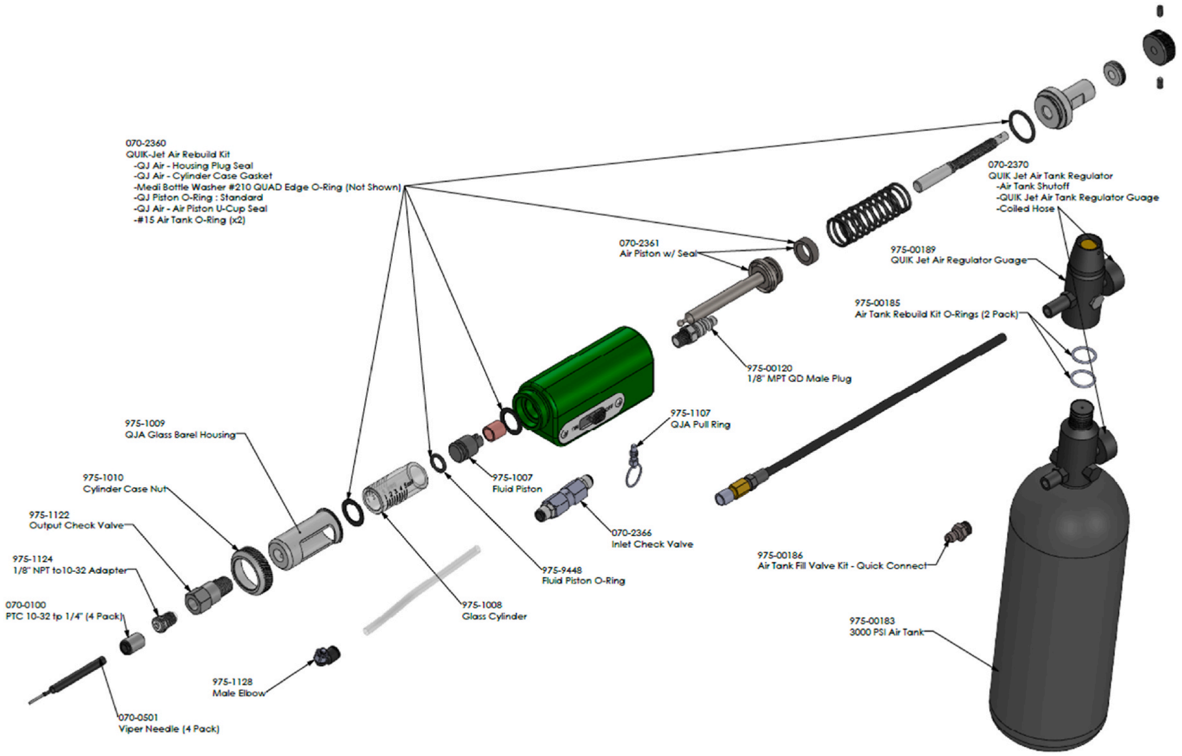

Fig. 8. Exploded view of Quik-jet AIR injection system (Arborjet Inc, Woburn, MA, USA). Note: From QUIK-jet Kit by Arborjet, 2022 (https://arborjet.wpenginepowered.com/wp-content/uploads/2018/05/Quik-Jet-Customer-Drawing-2-1.pdf) Copyright 2022 by Arborjet, Inc.

Fig. 9. **A.** Ecoject injection system (Lallemand, Ontario, Canada). Note: From EcoJect Microinjection System by Lallemand, 2023 (https://bioforest.ca/en/canada/product-details/ecoject-microinjection-system/) Copyright 2023 by Lallemand, Inc. **B.** TREE IV (Arborjet Inc., Woburn, MA, USA) Note: From TREE IV by Arborjet, 2022 (https://arborjet.com/product/tree-i-v-2-pack-kit/) Copyright 2022 by Arborjet, Inc. **C.** Mauget microinjection capsule (Mauget, Arcadia, CA, USA) **D.** Tree tech microinjection capsule (Tree tech microinjection system, Morriston, FL, USA).

injection system used a double-acting cylinder, eliminating the need for a compression spring. The cylinder is fitted to a solution pumping cylinder such that the compressed gas powers the supply and recharge of the solution in the pumping cylinder. However, this design leads to gas depletion on the extension and return stroke of the hydraulic cylinder. A unique feature of Brown's (1978) design is a stroke-adjusting assembly, which allows a precise, adjustable volume of solution to be injected into the injection site.

The QUIK-jet Air (Arborjet Inc., Woburn, MA, USA) is modified from the QUIK-jet® injection device to apply pressure to the piston via a compressed air tank. Unlike previously mentioned air pressure devices, the QUIK-jet Air features a compact design that can be entirely carried by hand (Fig. 7B). It features compression springs to automatically refill the glass barrel and a mechanism for adjusting the volume injected. Other components of the device are shown in Fig. 8. The use of QUIK-jet Air involves the process of drilling, plugging the injection site, and injecting the solution. Since the injection device cannot be left in the injection port and cannot be used to deliver the solution to multiple injection sites at once, the user has to wait until the injection is completed at each injection site. Moreover, the injection needle must be used with Aborplugs, which have known issues described previously.

The Ecoject injection system (Lallemand, ON, Canada) (Fig. 9A), similar to Filer's injection apparatus (Filer, 1973), is used to fill injection canisters (at 0.69–1.03 MPa) that dispense the pressurised solution into injection ports via the Ecoject nozzles. However, the Ecoject also houses the compressed gas in the same container as the injected solution, potentially leading to the compressed gas dissolving into the injected solution. A similar device is the TREE IV (Arborjet Inc., Woburn, MA, USA) (Fig. 9B), where a prefilled injection bottle is air pressured (0.2–0.41 MPa) with a bicycle pump before injecting the chemical solution into the tree. Components of the device are found in Fig. 10. The device can be used for multiple injection sites and also requires the use of Arborplugs.

The Mauget microinjection device (Mauget, Arcadia, CA, USA) (Fig. 9C) is sold as a small amount of air-pressurised therapeutic solution in a capsule and delivered to the tree via feeder tubes. The device promotes a closed chemical application system and the user does not have contact with the chemical during injection. A similar device is the Tree Tech microinjection device (Tree Tech Microinjection System, Morriston, FL, USA) (Fig. 9D), but both devices are nonreusable and operate under low pressure, implying that the injection rate can be slow when

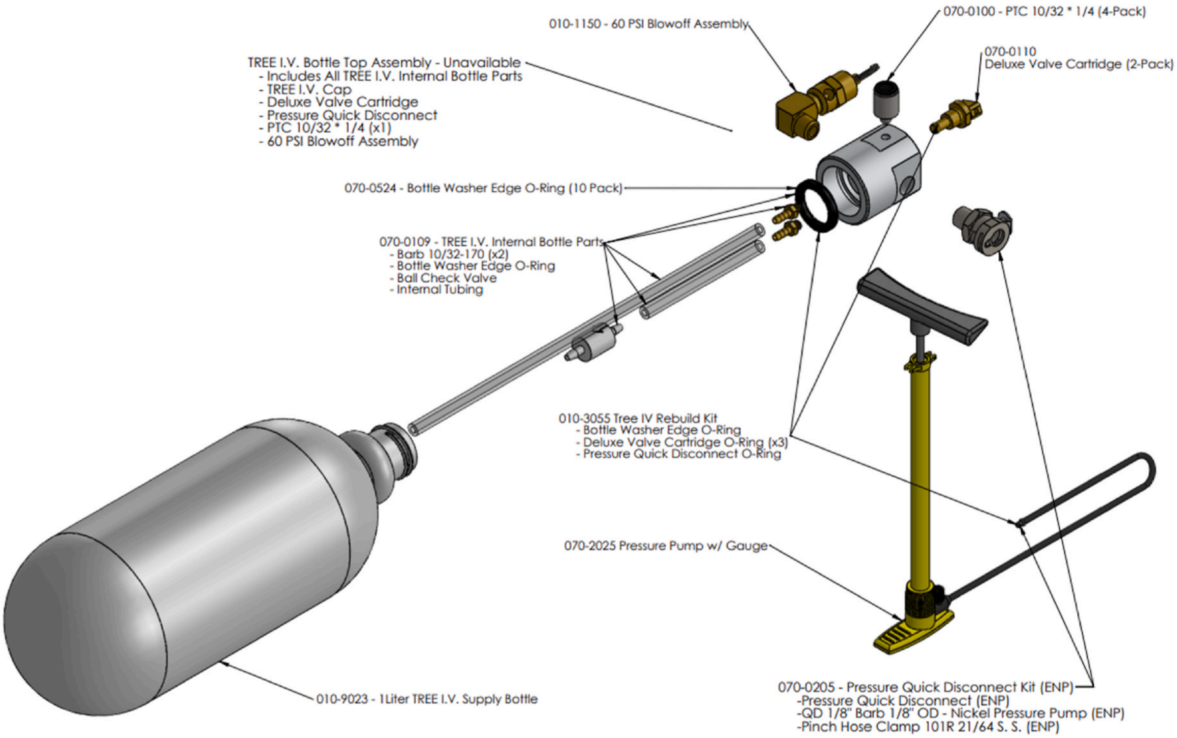

Fig. 10. Exploded view of TREE IV injection system (Arborjet Inc, Woburn, MA, USA). Note: From TREE IV by Arborjet, 2022 (https://arborjet.wpenginepowered.com/wp-content/uploads/2018/03/Tree-IV-Original.pdf), Copyright 2022 by Arborjet, Inc.

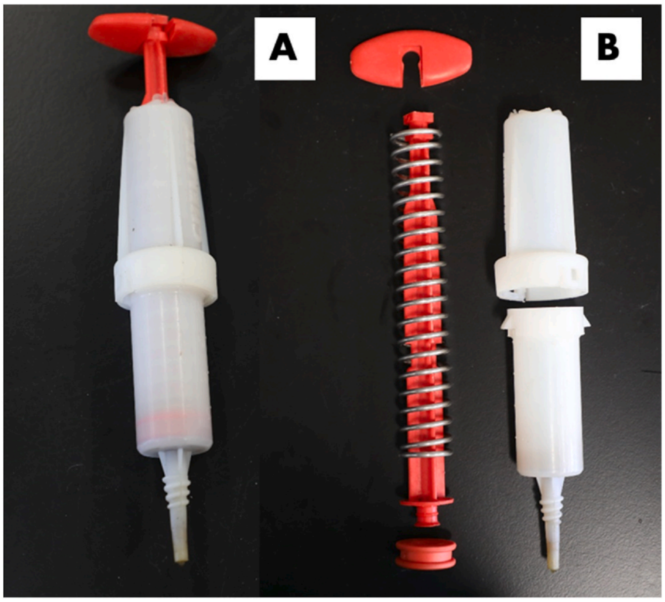

Fig. 11. A. ChemJet® Tree Injector (Chemjet Trading Pty. Ltd., Banyo, QLD, Australia) **B.** Exploded view of the ChemJet® Tree Injector showing the plunger handle, compression spring, plunger stem, rubber seal, body, and nozzle.

conditions are unfavorable.

Compressed gas is the most commonly used pressure source (Table 1). However, the downside of using compressed gas as a pressure source is that the gas gets depleted over time, requiring the gas tank to be repressurised after multiple uses. Also, pressure from compressed air does not compensate for resistance to flow; instead, the pressure from the compressed gas is reduced after every use (West, 1999). Other compressed air systems include injection devices proposed by Sachs et al. (1977), Brown, (1978), Phair & Ellmore (1984), and Helson et al. (2001), as well as Arborchem (Fuchs, 1988), Systemic tree injection tubes (Helson et al., 2001), TREE I.V. Fseries (Arborjet Inc., Woburn, MA, USA), and Q-connect (Rainbow Ecoscience, Minnetonka, MN, USA) (Table 1).

3.2.1.3. Compression spring. The ChemJet® Tree Injector (Chemjet Trading Pty. Ltd., Banyo, QLD, Australia) is a compact design that supplies 20 ml of therapeutic material at a working pressure of 0.1–0.15 MPa (Fernando et al., 2013) and combines the idea of an injector screw (screw at the tip) and a needle (Fig. 11). The device is screwed into predrilled holes and the plunger is released to begin injection. The ChemJet® Tree Injector is easier to use, has fewer components, and is a relatively cheaper alternative to the air pressure methods. It can also be left attached to the tree during the injection process, allowing other injectors to be used simultaneously at multiple injection sites. A similar device is the Stallion 75 injection tubes (Fuchs, 1988) with a downside that it does not feature a plunger for self-filling, requiring a pressurised bulk loader to fill the injection tube. The downside of using a compression spring as a pressure source is that the pressure applied is only at its maximum when the spring is fully compressed and pressure decreases as the spring extend, slowing down the injection process. This is compounded when considering that resistance to injection also tends to increase as more volume is injected into the tree.

3.2.1.4. Elastomer. Pinkas et al. (1973) utilised the internal pressure of an inflated surgical latex tubing (internal diameter: 6.3 mm, wall thickness: 2.4 mm) to supply chemical solutions to apple trees at a starting pressure of 0.14 MPa. After sealing one end with a wire, the 0.4 m-long piece of latex tubing was filled with 500 ml of the fungicide solution using a hypodermic syringe. Injection was performed by drilling two holes, 11 mm in diameter and 60 mm deep, on opposite sides of the tree, 0.35 m above the soil surface, and the ends of the tubing were inserted into the drilled holes using a plastic wall plug (Fig. 2E). Navarro et al. (1992) used a device similar to Pinkas et al. (1973). The apparatus

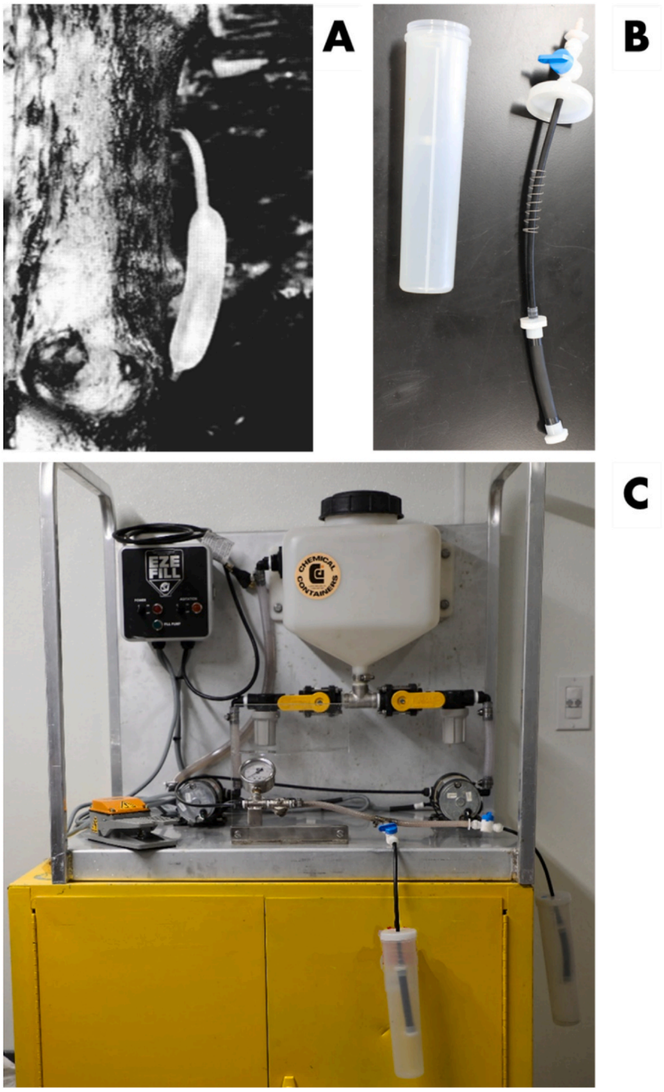

Fig. 12. **A.** Navarro injection device (Navarro et al., 1992).**B.** Exploded view of the injection device (TJ Bio Tech LLC, Lakeland, FL, USA) showing the plastic casing, elastic tube, spring, valve, and nozzle. **C.** Pump mechanism for injection device (Chemical Containers Inc., Lake Wales, FL, USA).

consists of a latex tube and a plastic injector inserted into predrilled holes (Fig. 12A) and provides a pressure range of 0.06–0.08 MPa when the tube is inflated with the chemical solution.

A recent device, Flexinject injector (TJ Bio Tech LLC, Lakeland, FL, USA) (Fig. 12B), also uses an inflated elastic tube as a pressure source. As an improvement on the Pinkas et al. (1973) and Navarro et al. (1992) design, it encloses the elastic tube in a plastic container, making it impervious to external disruptions. The injector tube is inflated using a pump (Chemical Containers Inc., Lake Wales, FL, USA) to supply a specific volume of solution into the elastic tube and is sealed using a valve before inserting it into an injection port (Fig. 12C). The valve is then opened to release the injectate at a pressure of 0.26 MPa. However, the elasticity of the inflated tube declines over time, and sometimes bursts during filling, transportation, and use (*pers. comm. with FL citrus growers*).

3.2.1.5. Pump pressure. Himelick (1972) retrofitted a hydraulic sprayer (John Bean sprayer, FMC Corporation, PA, USA) equipped with a pressure regulator and the capacity to provide agitation to the injected solution. The sprayer consists of a gasoline-powered positive displacement piston pump that supplies chemical solutions to injection screws at a peak pressure of 0.28 MPa.

The sidewinder tree injector (Sidewinder Precision Tree Injectors, Loganholme, QLD, Australia) features an efficient design such that a single device (Fig. 13A), the rotary injector head (Fig. 13B), is used for drilling, inserting the injector screws, delivering the therapeutic solution, and plugging the hole after treatment. Unlike Himelik's displacement pump, the sidewinder injector uses a dosing pump activated by a handle to dispense between 5 and 15 ml per handle swing, enhancing the precision in the therapeutic solution applied. It operates under a maximum pressure of 4.8 MPa (Smith & Smith, 2000), allowing quick injection. However, a drawback of the sidewinder is that it cannot be used to inject multiple trees at once.

Although a pump may be a more expensive alternative pressure source, it has the advantage of compensating for resistance to flow by increasing the pressure applied until the maximum pressure is reached. Pumps are also non-depletable, unlike compressed air, and have a longer lifespan than elastomers and springs. However, a metering pump with an adjustable pressure and flow rate is recommended since different species exhibit varying absorption rates (Montecchio, 2013; Sachs et al., 1977).

3.2.2. Non-pressurised injection

Non-pressurised injection relies on atmospheric pressure and sap flow to absorb applied chemicals (Montecchio, 2013; Sachs et al., 1977), requiring longer application times. However, Montecchio (2013) was

Fig. 13. **A.** Sidewinder tree injector system (Sidewinder Precision Tree Injectors, Longholme, QLD, Australia). **B.** Rotary injector head showing attached pressure gauge. Note: From SideWinder's Precision Chemical Tree Injectors by Tree Injectors (https://treeinjectors.com/blog/patented-combination-drill-injector/- accessed February 2024), Copyright ©2023 Tree Injectors, Longholme, QLD Australia.

Table 2
Injection parameters used by researchers for different species.

Reported injection parameters								
Trees injected	Trunk diameter (mm) (measured height (m))	Injection height (m)	Injection port diameter (mm)	Injection port depth (mm)	Number of ports	Pressure of injection device (MPa)	Devices used	References
American elms (8-year-old), Green ash and White ash	70 - 104 (3.50 m)	0.15	15	40	1–3	0.11	Solution was supplied through spiles (Holmes, 1982), Systemic Tree Injection Tubes	(Holmes, 1982; Mota-Sanchez et al., 2009)
Almond, Apricot, Common apple, English walnut, European plum, Grapefruit, Japanese plum, Mandarin, Olive, Peach, Pear, Sweet orange, Chinaberry, Common oleander, Eastern sycamore, Elm, Flame bottle tree, Globe elm, Glossy privet, Horsetail tree, White poplar, Holm oak, Murray red gum and Ash	87–398	0.20–0.40	4–6	50	3	0.06–0.08 (Zamora & Escobar, 2000), 0.31 (Smitley et al., 2010)	Navarro et al. (1992) injection device, QUIK-jet (Smitley et al., 2010; Wise et al., 2014), TREE I.V. (Smitley et al., 2010)	(Smitley et al., 2010; Wise et al., 2014; Zamora & Escobar, 2000)
Maritime Pine	214–236	0.20	9.5	100–120	Low-dose rate: 2, 3 and 4 holes for ≤220, >230 and > 330 mm DBH respectively Mid-dose rate: 3, 4, and 5 holes for ≤160 cm, >170, and >220 mm DBH respectively High-dose rate: 4 holes per tree	0.41 for the TREE IV (high dose rate)	QUIK-jet and TREE IV.	Sousa et al. (2013)
Red maple, Eastern white pine, Red oak, Eastern hemlock, White birch, Black birch, American chestnut, White ash and Weeping willow	50 - 250 (1.40 m)	"lower trunk and root flare areas"	6	6–12	Not specified	0.1	Mauget microinjection capsules	Tattar and Tattar (1999)
American elms	406 - 889 (1.37 m)	"as close as possible to ground level"	Not specified	6.35	Variable: ports drilled 101.6–152.4 mm apart	up to 0.34	Phair and Ellmore (1984) injection device	Phair and Ellmore (1984)
White ash and Green ash	40–50	0.1 m above graft union	8	15	1	0.2	Systemic Tree Injection Tubes	Tanis et al. (2012)

able to hasten absorption by using an injector with a lenticular biconvex blade to dispense the injected solution. The inserted blade induces a temporary constriction of the xylem vessels on both sides of the blade, such that a venturi effect occurs, characterised by a reduction of sap pressure and an acceleration of sap velocity, so that when transpiration rates are high, the tree can passively uptake the solution faster.

Non-pressurised injection may be more suitable for trees with damaged bark or dead areas on the trunk (Reil, 1979) and has been recommended for species with minute wood pores (Sachs et al., 1977). However, non-pressurised injection is not suitable for dormant deciduous trees, is prone to external disruptions because it has to be left connected to the tree for extended periods (i.e. days) and is not suitable for antibiotics that deteriorate over time.

4. Optimum injection parameters

The placement of injection ports plays a critical role in determining the rates of injection and distribution. Typically, the wood from actively growing sections of tree trunks exhibits greater vessel size, thereby presenting lower resistance to the injection of solutions (Sachs et al., 1977).

Brown and Bachelor, (1974) conducted preliminary experiments that showed that injection rate increased with hole size, injection pressure, and tree diameter. Brown and Bachelor, (1974) found that injection rate was not significantly affected by leaf water potential and was higher for drilled holes than punched holes. The following sections discuss the question of optimal diameter, depth, injection height, number of holes, pressure, and injection rate.

4.1. Diameter

The smaller the injection port, the less wounding to the tree and the lower the risk for infection. Archer & Albrecht (2023) showed that injection port diameter, rather than depth, determined secondary injury (i.e. an increase in wound size and bark crack) for Valencia orange trees. Injection port diameter is also a function of the dispensing nozzle and should be slightly smaller than the dispensing nozzle or hole plug to ensure a tight seal. If the injection port is predrilled, the nozzle has to be optimised to minimise resistance to flow by using an inner diameter that is not too small while also minimising injury to the tree by using an outer

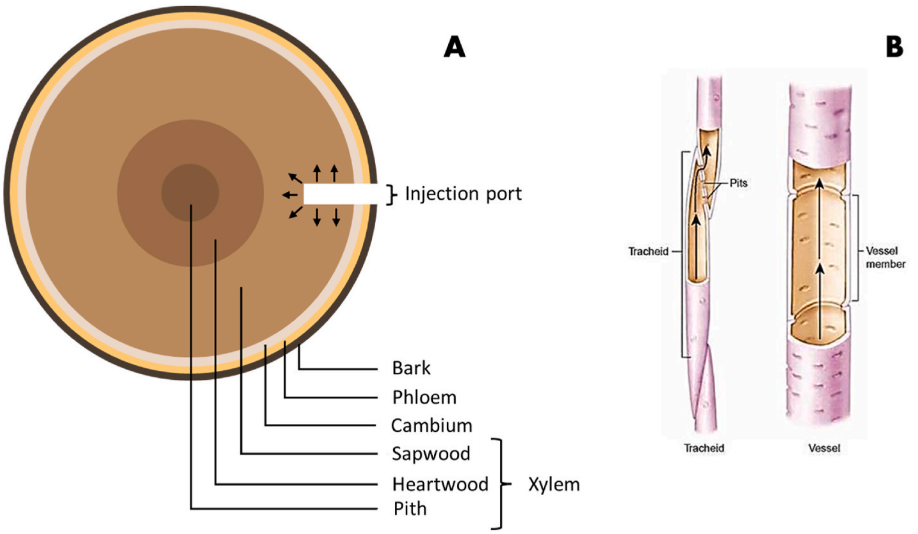

Fig. 14. **A.** Cross section of a stem showing injection port depth and diameter. **B.** Sap flow through the main conducting cells in gymnosperms (tracheids) and angiosperms (vessels) (Johnson & Raven, 2002).

Table 3
Classification of trees according to their hydraulic architecture.

Species hydraulic architecture							
Species			Examples	Main conducting cells (length, diameter) Tissue: Xylem	Approximate range of permeability (m^2)	Concentration of hydric activity	References
Gymnosperms	Conifers		Pines, Cedars, Firs, Spruces, and Larch trees	Tracheids (up to 5 mm in length, 10–20 μm in diameter)	10^{-14} to 10^{-12}	Spans across most of the sapwood rings	(Chaney, 1986; Comstock, 1970; Domec et al., 2007; Kozlowski et al., 1967; Siau, 1984)
Angiosperms	Dicots	Ring porous	Oak, Elm, Ash, and Chestnut trees	Vessels (up to 10 m in length, 10–200 μm in diameter)	10^{-13} to 10-^{10}	90 % in the current annual ring	(Berger & Laurent, 2019; Chaney, 1986; Domec et al., 2007; Kozlowski et al., 1967; Siau, 1984; Yin et al., 2023)
		Diffuse porous	Apple, Peach, Plum, Cherry, Citrus, Pear, Apricot, Fig, Sycamore, Poplar, Willow and Maple trees	Vessels (up to 18 m in length, 10–500 μm in diameter)	10^{-14} to 10^{-12}	70 % in the current annual ring	(Berger & Laurent, 2019; Chaney, 1986; Domec et al., 2007; Kozlowski et al., 1967; Siau, 1984; Yin et al., 2023)

diameter that is not too large. If the trunk has to be punctured by a needle, the needle geometry has to be optimised to maximise resistance to bending, minimise resistance to flow, and minimise injury to the tree. Bark thickness can also be a bench mark for determining the diameter of the injection port, especially for shallow injection ports; for instance, while trying to prevent leaks during high-pressure injection, Himelick (1972) discovered that a 15.88 mm diameter injector screw was optimal for treating large trees with 6.35–12.70 mm bark thickness.

Large-diameter injection ports are used because injection rate is directly proportional to the stem cross-sectional area exposed to the solution (Brown, 1978; Sachs et al., 1977; Zamora & Escobar, 2000). Examples of injection port diameters used in different studies are found in Table 2; other examples can be found in the work of Berger & Laurent (2019). The optimal hole diameter is the diameter that enables the highest injection rates and promotes the quickest wound healing and would likely vary depending on the tree species and injected chemical. In the case of pear (*Pyrus communis* L.) trees, Sachs et al. (1977) found this diameter to be within 6.3 mm and 12.7 mm for 50 mm deep holes while injecting different therapeutic materials. More studies are required to determine the optimal injection port diameter and the relationship between optimal hole diameter and the number of injection ports for different species and different tree sizes.

4.2. Depth

Managing insects that feed under the bark of trees, such as flat head borers (Smitley et al., 2010; Tanis et al., 2012) and bark beetles, or phloem-limited diseases, such as greening (Halbert & Manjunath, 2004) and pear decline (Lacy et al., 1980), requires a targeted delivery of therapeutics to the bark and phloem. However, it is impractical to inject into the bark without excessive leaks, and the intricate physiology and the thin layer of the phloem (Puttamuk et al., 2014) make it impossible to inject large volumes of therapeutic material into the phloem without irreparably damaging them and creating excessive leakages.

Although the target tissue for injection is the xylem, particularly the sapwood (Fig. 14A), it has been shown that the injected compound is redistributed within the tree, including the roots, phloem and bark (Hu & Wang, 2016; Roach, 1939; Tattar & Tattar, 1999). For angiosperms, the concentration of hydric activity in the xylem is in the current annual ring (Table 3). Annual rings have shallow depths, averaging in width from 0.6 mm to 2.5 mm in pine, spruce, beech, sycamore and oak trees (Essert et al., 2018; Larsen & MacDonald, 1995; Nicolussi et al., 1995; Rodríguez-Ramírez et al., 2019; Wild, 2013), making it difficult for pressurised injection into the current annual ring without leaks or blowouts.

While injection rate has been shown to increase with depth, experiments conducted on the inhibition of growth in 10-year-old peach trees through the injection of daminozide demonstrated minimal variation in the efficacy of the chemical when using injection ports at depths of 25 mm, 50 mm, or 75 mm (Sachs et al., 1977). This is probably because peach trees are ring-porous, and in ring-porous xylems, approximately 90% of the hydraulic activity occurs within the current annual ring (Table 3), making deeper holes appear to lack practical utility. However, this phenomenon suggests that non-functional xylem vessels can potentially function as a reservoir, facilitating the movement of solutions into the active xylem (Sachs et al., 1977), allowing for injection at depths greater than the current annual ring, thereby allowing the optimisation of the depth to minimise wounding and prevent leaks or blowouts.

Jones & Gregory (1971) used a hole depth that reached two or three annual rings for their high-pressure system, similar to Phair & Ellmore (1984). Examples of injection port depth used in other studies are found in Table 2, and more examples can be found in the work of Berger & Laurent (2019). Montecchio (2013) recommended a minimum penetration depth of 20 mm for angiosperms and greater depths for conifers and palms when using the BITE® Tool. The ideal depth will vary depending on the species, the injected chemical, and the need to prevent leaks based on the applied pressure and injection rate.

4.3. Above-ground injection height

Injection height affects material uptake and distribution (Kiss et al., 2021; Tattar & Tattar, 1999) due to the hydraulic conductivity gradient along the stem caused by the increasing diameter of water-conducting vessels and a simultaneous decrease in vessel density from leaves to roots (Aloni & Zimmermann, 1983; Zimmermann, 1983). The significance of increasing vessel diameter is illustrated by Hagen and Poiseuille's law, which states that hydraulic conductivity is proportional to the fourth power of the conducting capillary radius (Zimmermann, 1983), implying that the comparison of hydraulic conductivities along the stem should be made based on the fourth power of the conduit diameters. This indicates that for a given injection port size, significantly less pressure is required to inject a specific volume at the base of the tree compared to injection ports at increasing heights along the stem. Also, due to higher conductivity at the base, quicker translocation of the injected solution can be achieved.

Experiments conducted on 8-year-old walnut trees showed that injections performed in the lower third of the trunk were more effective than injections in the upper region (Kiss et al., 2021). Recommended or reported injection height differs across several studies (Table 2), ranging from breast height to ground level (Table 2, Jones & Gregory, 1971; Montecchio, 2013). However, Kiss et al. (2021) recommended that a sufficiently low injection height should be used to allow the active ingredient enough time to diffuse along the xylem before transport reaches the branches. Sachs et al. (1977) and Reil (1979) also recommended placing injection ports beneath primary scaffold branches to guarantee substantial delivery of the injected solution to those branches.

4.4. Number of injection ports

The lack of homogeneous distribution of the injected material using a single injection port has been reported by several studies (Aćimović et al., 2014; Hu & Wang, 2016);hence, the advantage of having multiple injection sites. Reil (1979) recommends that on trees with trunk diameters exceeding 406.4 mm, injection holes should be spaced approximately 152.4 mm apart along the trunk's circumference and advised that injection sites should be increased for trees with multiple scaffolds or multiple low-lying limbs. Similarly, Montecchio (2013) recommended one injection port per 250–300 mm circumference if the injection rate is slow (1 ml min^{-1}) or one port per 400 mm if the rate of injection is fast (10 ml min^{-1}) to ensure good distribution. Smitley et al. (2010) determined the number of injection sites by using the formula; DBH (mm)/50.8. Despite the aforementioned blanket recommendations, the number of injection ports must be based on the species' xylem anatomy. For example, the grain pattern of the xylem affects the homogeneous distribution of injected chemicals, determining injection spacing and depth, such that Elm trees with spiral grain need fewer injection points for homogenous distribution than straight-grain ash trees (Chaney, 1986). The pattern of spiral liquid movement along the trunk varies between and within species. Evaluating vascular integration in crop species is crucial for determining the optimal number of injection ports (Archer et al., 2022b). Other species that show the spiral movement of the injected substance include larch, spruce, and pine trees (Kozlowski et al., 1967).

Hu et al. (2018) conducted experiments that showed that two injection ports were optimum for 90–150 mm diameter, 5-year-old huanglongbing-affected citrus trees for oxytetracycline injection. Similarly, Reil & Beutel (1976) reported that three injection ports per mature pear tree were sufficient for ensuring uniform dispersion of solution within the tree for pressurised injection. Additional studies are required to determine the optimum number of injection ports based on tree species, tree age, injected chemical compound, and the method of injectate application, as well as studies that determine the relationship between maximum injectable volume for a given period based on the number of injection ports. This information may inform the choice of concentration levels to reduce the phytotoxicity of highly acidic therapeutic materials.

4.5. Injection rate and pressure

Pressure builds up when there is resistance to flow. A common misconception is that the pressure that is set at the pressure source, or the pressure characterisation of the pressure source, is the same pressure applied during injection. Injection pressure only matches the set or characteristic pressure at the source when there is zero flow, in which case, injection is not taking place. For pressure sources that decline in pressure over the course of application, i.e., compression spring, elastomer, and compressed gas, the applied pressure will always be less than the pressure characteristic of the source except if there is zero flow at the beginning of injection.

Injection systems that allow for a pressure increase to compensate for resistance to flow, i.e., pump pressure or hand pressure, can be used to show that pressure increase has a temporary effect on injection rate. Ojo et al. (2024) showed that increasing pressure did not reverse the decline in injection rate as the tree approached saturation when injecting Valencia orange trees and applying pressures as high as 6 MPa. Similarly, Sachs et al. (1977) showed that at low injection rates of less than 50 ml min^{-1}, an increase in pressure beyond 1.38 MPa did not increase the injection rate without creating leakage around the injection port or bark rupture at the cambial union when injecting large volumes into fruit trees, including apple, apricot, plum, pear, and almond. Brown (1978) also found that pressures higher than 1.37 MPa for injecting American elm led to bark blowouts on some trees, similar to findings from another study (Reil, 1979).

Deciduous species have a higher absorption rate, requiring lower pressure, especially when the solution is administered on a flat or convex surface near the tree's base or at the root collar (Montecchio, 2013). Coniferous species, including Monterey pine (*Pinus radiata)* and Canary Island date palm (*Phoenix canariensis*), exhibit minimal solution uptake even under pressures as high as 2.76 MPa (Sachs et al., 1977). This behaviour in conifers can be attributed to their unique wood structure, characterised by tracheids as the predominant cell type. In these tracheids, water movement occurs primarily through small, bordered pits in the side walls, as opposed to the vertical movement through open vessel ends, which are abundant in angiosperm wood (Fig. 14B). Sachs et al. (1977) suggested that trunk injection techniques that rely on gravitational flow might be the most effective approach for injecting chemicals into numerous species characterised by minute wood pores. However, applying pressure and increasing injection port size can significantly reduce injection duration, even for trees with slow sap dynamics. Montecchio (2013) showed that the up-take time of abamectin 0.1% and safranin to the leaves of palm trees (*Trachycarpus fortunei*) via a drill-free, non-pressurised system was reduced from 24 h to 3 h by using drilled holes and applying a pressure of 0.34 MPa. However, Reil (1979) cautioned to maintain pressure below 0.69 MPa when injecting apricot trees to prevent excessive gumming.

Disease infestation and turbidity also affect the injection rate and responsiveness to pressure increase. Himelick (1972) injected soluble chemicals into American elms at 75.7 ml s^{-1}, noting that American elm wilt disease reduced the injection rate by 16.7%. Injecting at an injection rate higher than the tree is able to absorb would lead to pressure buildup, and it may be necessary to reduce the flow rate to prevent blowouts or leaks. Ojo et al. (2024) also showed that injecting during irrigation events made injected trees more responsive to pressure increase, leading to higher volumes being injected into mature citrus trees.

Also important to note is that injecting at low pressures may lead to phytotoxicity. For instance, oxytetracycline and ferrous sulfate caused severe damage when applied using gravity flow and 0.1 MPa, but no phytotoxicity was observed when the same concentrations and rates were applied at 0.86–1.38 MPa (Reil, 1979). Optimal pressure would depend on the species, disease infestation, material injected, and injection port or injector (needle or injector screw) characteristics requiring further studies on specific parameters.

Trunk injection remains a more precise method of applying therapeutic materials compared to foliar spray and soil drench. However, advancement in precise and efficient dosage delivery of therapeutic materials to individual trees would require real-time multifactorial decisions based on tree volume, above-ground injection height, injection rate and pressure, diameter and depth of the injection port, and number of injection ports. For injection dosage, recommendations are usually made based on trunk diameter. However, real-time or a combination of real-time and offline tree canopy volume estimation using deep learning models (Ampatzidis et al., 2020; Partel et al., 2021) will enhance precise delivery.

For efficient delivery, the goal is to enhance homogeneous distribution, increase application speed, minimise tree wounding, and prevent leaks and blowouts during injection. Decision-making and optimisation efforts can be achieved using a machine-learning approach. However, tree-level optimisation efforts for efficient delivery may significantly complicate the injection process and not result in injection parameter variation. For instance, a small diameter trunk may optimally require a shorter injection port depth compared to larger trunks. However, the need to prevent leaks, especially for pressurised injection, may require that the penetration depth remains the same for different trunk diameters. A trade-off on complexity and extent of precision may involve sacrificing complexity for a more practical solution, optimising efficiency and effectiveness.

5. Other considerations

Other factors found to be important in the development and implementation of various injection devices include the prevention of leaks, wounding, exclusion of air during injection, and variability of stem hydraulic conductivity.

5.1. Variability

Variability in injection characteristics, such as the injection rate and maximum pressure required to inject a specific volume, begins at the tree level and can be significantly different. For instance, the injection rate at different locations of 12 to 15-year-old American elm trees varied by 25–40% of the mean rate (Brown, 1978; Brown & Bachelor, 1974). Sachs et al. (1977) attributed the within-tree variability in injection rate while injecting several fruit and landscape trees to the wood structure variation at different positions of the same stem. They recommended that each injection port feature a metering device when injecting multiple ports from a single source to guarantee a uniform volume of solution for every port, irrespective of any port resistance encountered, while Jones & Gregory (1971) and Brown and Bachelor, (1974) recommended individual shut-off valves for each injector. Injecting equal volumes to each injection port would enhance homogeneous distribution within the trunk. However, this could slow the injection process due to significant radial variation in specific hydraulic conductivity, especially since increasing pressure may not yield a significant flow increase. Injecting smaller dosages across multiple injection sites may solve this problem.

5.2. Leaks and backflow

Preventing leaks is perhaps the most critical factor for successful injection, especially in pressurised injections. While injecting at a pressure range of 0.67 MPa–1.38 MPa, Brown (1978) prevented leaks by inserting the nozzle to a minimum depth of 12.5 mm and using a 5.59 mm diameter nozzle that was slightly larger than the hole diameter (5.41 mm) thereby ensuring that the withdrawal force of the nozzle was several times greater than the hydraulic force of the injected liquid that pushes against it away from the hole. Similarly, Wilson et al. (1977) used a 12-gauge needle (2.769 mm diameter) for a 2.38 mm diameter drilled hole to ensure a secure and effective seal. Brown (1978) noted that the forced fit did not cause the splitting of the xylem or the loosening of cambial tissue. The drill-free mechanisms of Montecchio (2013) and Jones & Gregory (1971) used a gasket to prevent leaks. Montecchio (2013) suggested that it may be necessary to smooth the bark surface using a knife or to move the injection site a few centimetres to one side when the bark is too rough or too curved to ensure a proper seal. Himelick (1972) recommended that rotating an injection screw further inward would stop a blowout through a bark crack above or below the injection site. Ojo et al. (2024) using a drill-free system, radially positioned outlet holes at the tip of the needle to eliminate leaks during injection.

To prevent backflow during high-pressure injection, Sachs et al. (1977) used check valves while forcing large volumes of chemical solutions into fruit and landscape trees. Similarly, Reil and Beutel (1976) recommended that quick couplers have a check valve as a preventive measure against backflow after treatment. In pressurised injection, backflow from the tree can also occur after the injection process is completed. Brown (1978) observed that the injector could be promptly extracted from sycamore and elm trees without experiencing any backflow, but a 2-min delay was necessary when dealing with other landscape species. Similarly, Reil (1979) suggested waiting until the tree absorbs the liquid before removing the injector screw, which can take between 30 s and 5 min, depending on the tree species and the time of year. Backflow after injection is closely related to applied pressure during injection. Applying excessive pressure during injection would lead to backflow after the injection is completed. Experiments that determine the maximum pressure for the required injection volume should be performed to determine the cut-off pressure. Reducing the flow rate and increasing nozzle or needle penetration depth is recommended if leaks occur during injection.

5.3. Exclusion of air during injection

While some studies did not exclude air from the injection port (Brown, 1978; Himelick, 1972; Sachs et al., 1977), others have recommended excluding air. Montecchio (2013) for example, used a syringe plunger to remove air from the injection site, stating that treatment would be slower if the air was not first drawn out. Similarly, Jones & Gregory (1971) excluded air through a loose pipe union while allowing the injected solution to flow through the supply line via a gate valve under low pressure. However, Himelick (1972) did not attempt to fill his 12.2 m injection hoses with solution prior to injection and at an injection

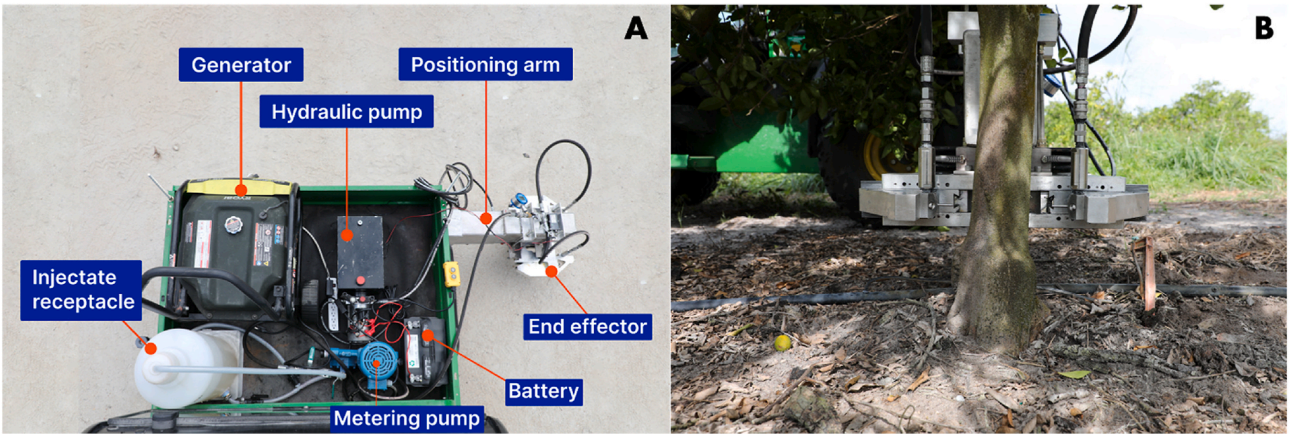

Fig. 15. **A**. Top view of the automated injection system (Ojo et al., 2024) **B.** End effector showing radially positioned needles before injection to a citrus tree trunk.

rate of 75.7 ml s^{-1}; he confirmed using a dipstick, the volume injected. In general, most non-pressurised systems exclude air during injection, given that the presence of air would further slowdown injection, while pressurised systems are not reported to be adversely affected by the exclusion of air. While species differ considerably in their ability to resist air pockets within the xylem (embolism) (Koepke & Kolb, 2013), embolism lowers hydraulic conductivity, adversely affecting plant development and occurs naturally when plants undergo severe water stress (Lens et al., 2013). However, an air injection experiment conducted by Hao et al. (2013) showed that plants refilled embolised vessels under positive root pressure, similar to findings from Hacke & Sauter (1996) and Améglio et al. (2002), suggesting a minimal need to exclude air during injection. However, air in the flow line can give false injected volume readings, increase the required pressure for injection due to energy loss from air pockets in the fluid, and reduce the injection rate. Misleading injection and pressure rates from air pockets trapped in the injection line can be avoided by using an automatic air release valve to ensure an airtight flow system.

5.4. *Wounding*

Injection wound is first a function of the hole size (diameter and depth) of the injection port. However, depending on the type of injection device and material injected, wound size and resulting bark crack may vary significantly and increase in size over time before wound closure occurs (Archer & Albrecht, 2023; Hauer et al., 2022). Montecchio (2013) compared an injection port created using a drilled hole to a larger port created by a drill-free lenticular blade. The results showed that the smaller drilled hole was noticeably necrotic after four weeks, while the wound from the larger lenticular blade was effectively closed by meristematic tissues. Similarly, Aćimović et al. (2016) compared drill-based and drill-free tree injection methods for wound closure on apple trees. Drill ports either sealed with Arborplug® (Arborjet Inc., MA USA) or unsealed were shown to take longer to heal than a drill-free lenticular port. Unlike drilling, the lenticular blade (BITE® Tool) does not remove the cambial and woody tissues but separates them with minimal friction and damage (Montecchio, 2013). Drilling also causes the edges of the hole to compartmentalise (Montecchio, 2013). Archer & Albrecht (2023) compared injection via QUIK-jet Air, ChemJet® Tree Injector, and a custom-made non-pressurised injection system, comparing oxytetracycline, imidacloprid, and water injection on 5-year-old Valencia orange trees. The injection port for QUIK-jet Air was the largest and resulted in the largest external wound size and compartmentalisation area, with the least being the non-pressurised injection system with the smallest injection port. Among all injection techniques, oxytetracycline injection resulted in the largest external wound size, the largest compartmentalisation zone, the slowest wound closure, and the most internal discolouration, with water injection resulting in the least wound size area and area of compartmentalisation (Archer & Albrecht, 2023). Avoiding the use of plastic plugs that remain attached to the tree and using smaller diameter ports are recommended to reduce wounding.

Jones & Gregory (1971) recommended that wound dressing be applied to the injection site after injection. However, Reil (1979) observed that untreated holes exhibited fewer decay issues and faster healing than holes treated with a sealant, similar to findings from other studies (Hudler & Jensen-Tracy, 1955; Neely, 2022; Shigo & Shortle, 1984). Studies have shown that living tree cells react to injuries and parasites by releasing substances like gums and lignin precursors and grow into the vessel lumens to form tylosis, limiting pathogen spread within the xylem (Tyree & Ewers, 1991; Zimmermann, 1983).

6. Automated injection system

Trunk injection has shown remarkable success in landscape trees and orchard management. However, existing trunk injection methods are manually operated, posing implementation challenges for large-scale production (Hu & Wang, 2016; Li & Nangong, 2022). Ojo et al. (2024) developed an automated trunk injection system that is drill-free and pressurised to carry out rapid trunk injection (Fig. 15 A & B). The injection system is mountable to a farm vehicle and consists of a retractable positioning arm that controls the movement of an end effector that forces injection needles into the tree and supplies therapeutic material to both sides of the tree trunk. Other components of the injection device are shown in Fig. 15A.

Unique features of the injection device are a simultaneous multi-puncture mechanism so that both sides of the tree are penetrated and injected at the push of a button and a metering pump with adjustable pressure and flow rate, allowing for user-defined injection rate and maximum pressure. It also features a small diameter needle (3.81 mm) to reduce wounding to the tree. Successful injections were performed at a fixed height of 200 mm from a flat ground surface and needle penetration depth of 25.4 mm on citrus trees while injecting up to 243 ml of water without leaks or blowout at application pressures up to 6 MPa for a set flow rate of 3.6 ml s^{-1}. Injection duration ranged from 30 s to 72 s for all trees. Although this novel technology is fast-acting and reduces the labour required for completing injection, it is still undergoing development to improve the reusability of the injection needle, the operation of the end effector, and automation of the positioning arm. An artificial intelligence (AI) enhanced sensing system to detect the tree trunk and the desired injection point, and to estimate the tree canopy volume, and hence, the amount of the injected therapeutic materials, in real time is under development. Based on this sensing system, a smart controller will automatically operate the positioning arm and the end effector, and select the optimal injected volume, flow rate, and pressure.

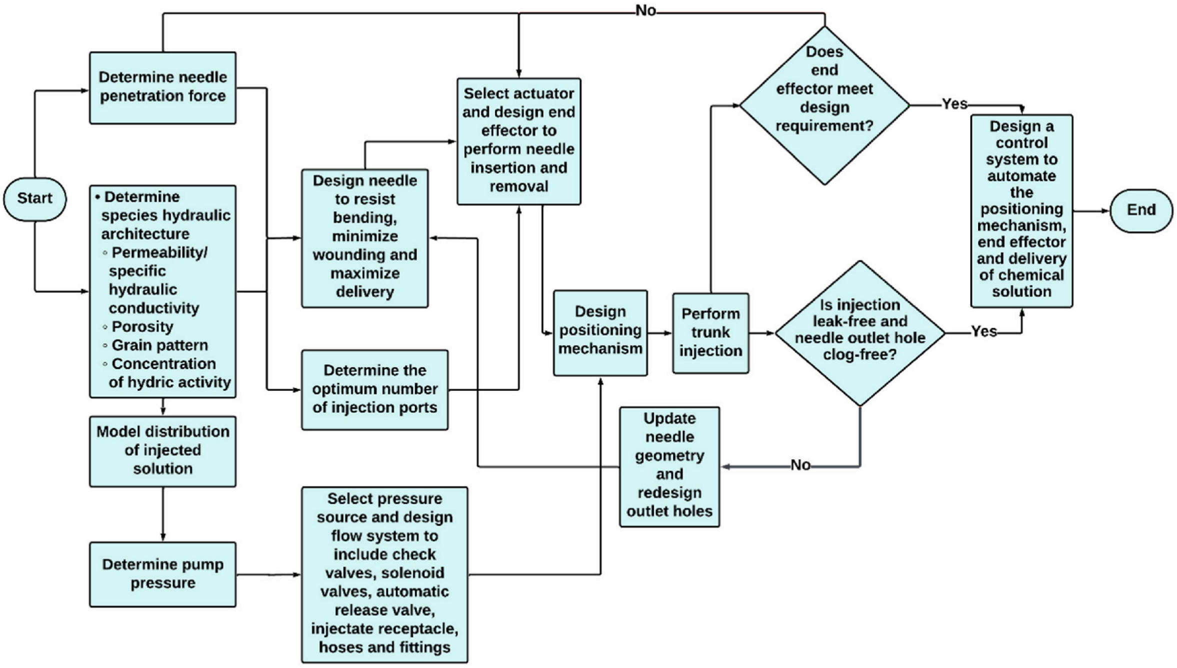

Fig. 16. An example process for automating a needle-based pressurised injection system.

7. Discussion and future perspectives

Trunk injection is an efficient method for treating vascular pests and diseases (Archer et al., 2022b; Ferreira et al., 2023), offering advantages such as reduced environmental impact, chemical waste minimisation, and increased chemical efficiency. The advantages and advancement in trunk injection technology have created a path for broader application of the intravascular approach to manage tree crops. However, mainstream adoption of trunk injection depends on mitigating certain drawbacks.

A primary concern is the tree wounding and associated secondary injuries, leading to the preference for drill-free systems (Aćimović et al., 2016; Perry et al., 1991). If injection is to be repeated periodically, it will be necessary to minimise wounding to the tree. A study modelling the interaction between injection port size and delivery characteristics for different tree species would inform tree injury minimisation. A lack of homogeneous distribution of injected compounds is another concern for trunk injection systems. It can lead to therapeutic concentrations in some parts of the tree that are too low, enabling the adaptation of disease vectors to become tolerant (Berger & Laurent, 2019), or concentrations that are too high in other parts that lead to phytotoxicity (Reil, 1979). This effect can potentially undermine treatment and enable bacterial resistance to antibiotics. Studies that determine the optimum number of injection ports based on tree age, species, and injected chemical compounds could help to achieve a homogeneous distribution of the injected therapeutics within the tree.

Implementation challenges for large-scale application of trunk injection on commercial farms stemming from slow application rate and substantial labour requirements promote a preference for pressurised systems and a need for automation of the injection process (Aćimović et al., 2014; Hu et al., 2018; Montecchio, 2013). An example procedure for the automation of a drill-free system is presented in Fig. 16. The development of sensors such as flow meters and solenoid valves that can be easily programmed to deliver fixed volume to each injection port and the use of deep learning algorithms for estimating tree-specific dosage based on canopy size or tree volume or algorithms that inform injection into preferred areas on the trunk would be helpful to achieve the goal of automation. Also, studies that model the distribution of injected compounds within the xylem of different species based on applied pressure would help in the estimation of injection pressure. Despite automation, the tree-by-tree process of trunk injection makes it challenging to scale to a rate comparable to traditional disease control methods. However, developing autonomous injection systems capable of communicating with each other is a promising strategy to achieve accelerated large-scale trunk injection. In the future, a fleet of AI-enabled automated or fully autonomous systems could be used to reduce the injection time and application costs, especially in large orchards. A high-level and adaptive multi-robot coordination is needed to optimize the task planning and control of the fleet of robots.

8. Conclusion

The application of plant protection products via trunk injection has continued to capture the attention of researchers and growers as an attractive alternative to conventional chemical application methods for pest and disease control. Over the decades, the design requirement for a trunk injection device has covered the need to be leak-free, portable, fast-acting, affordable, effective, and to minimise wounding to the tree, which has led to the development of different prototypes with their corresponding pros and cons.

Species and tree-level variation in injection characteristics require species-specific research to determine optimal injection port diameter, depth, number of injection ports, and the relationship between maximum injectable volume based on the geometry and number of injection ports to inform the design of an efficient trunk injection system.

Most trunk injection devices developed to date use compressed gas as a pressure source and are drill-based. There is a need to develop more drill-free injection systems that use a non-depletable pressure source with variable pressure and flow rate capabilities that are able to compensate for resistance to flow. The assumed goal is that trunk injection would be deployable at a speed comparable to conventional chemical control methods, and an automated trunk injection system would be a significant step in meeting that objective. Perhaps the deployment of a network of autonomous injection systems that can communicate with each other will be the full realisation of that goal.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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