

Road from R&D to innovation: The challenges and perspectives of trunk injection technology

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ABSTRACT

The European Union has introduced strict regulations requiring a reduction in pesticide usage, which can be reached by implementing new innovative technologies in agriculture. Trunk injection represents an alternative plant protection method that offers numerous advantages and aligns with sustainability goals.

The objective of the research is to provide a comprehensive overview of the history and current status of trunk injection development, and to present its innovation challenges and to examine the potential for commercialisation based on farmers' perceptions. The research methodology used both qualitative and quantitative tools. The current state of research and development (R&D) in Hungary, the advantages and risks were explored through expert interviews. Based on the results of this, the opinions of Hungarian walnut and cherry farmers as potential users of the technology are investigated through a questionnaire survey ($N = 80$).

It can be concluded that, although trunk injection technology has a long tradition and history, its uptake varies widely around the world. The diffusion of the technology is not facilitated by the strict regulations of the European Union, and R&D is a slow and costly process. However, it is encouraging that farmers are open to the new technology and demand its use.

KEYWORDS

trunk injection, plant protection technology, adopting innovation, innovation in agriculture, R&D in agriculture

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INTRODUCTION

The European Union is expecting more from farmers to ensure sustainability and protect the environment. One aspect of this is the need to significantly reduce pesticide use ([European Green Deal, 2023](#)). This can be achieved by using innovative new technologies and reforming plant protection processes. To meet these requirements, successful research and development (R&D) and innovation processes must be in place in the EU. This paper examines trunk injection technology from an innovation management perspective.

First, the research presents the theoretical background of innovation adoption and describes the development of trunk injection technology for plant protection, based on the literature. R&D of trunk injection technology is also being conducted in Hungary, primarily in walnut and cherry farming. The research aims are to explore and present 1) the technological innovation's challenges and 2) commercialisation perspectives based on the perceptions of prospective users, i.e. farmers. Qualitative and quantitative methodological tools are both employed: expert interviews and a questionnaire survey. The visualization and evaluation of the results is supported by a SWOT analysis.

THEORETICAL BACKGROUND OF INNOVATION ADOPTION

The distance between the conceptualization and implementation of an idea within a business context can be considerable. It may necessitate some fundamental research. Its operation must be proven (proof of concept), a prototype must be created and tested in different environments. The Oslo Manual ([OECD, 2018](#)) defines innovation as „a new or improved product or process (or combination thereof) that differs significantly from the unit's previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process)”. In other words, the term *innovation* is used to describe a product or process that has already been launched onto the market.

How long it takes to reach innovation from R&D, how many steps and how many risks it has, is quite different in each industry. The stages are typically aligned with the widely adopted Technology Readiness Level (TRL) classification system ([NASA, 2010](#)). It shows the technological view, but this paper highlights, that it is not enough to develop innovative solutions, they must also be adopted and spread. Farmers, as consumers of innovation, must be receptive to new technologies, which progress through three stages: acceptability, acceptance, and adoption. The Market and Technology Maturity Model (MTMM) integrates a technology-based TRL classification with consumer acceptance ([Silberer et al., 2023](#)). Adoptability can depend on internal factors such as the attitude of management ([Tóth et al., 2020](#)), and some external factors affecting the agricultural industry.

But how does adoption work? Is it just a matter of time and happens by itself? It is not the case that a newly developed technology is introduced to the market and then all relevant actors switch to it overnight. On the one hand, it helps the process if we do not only rely on internal resources (linear innovation model), but open innovation and involve our partners ([Chesbrough, 2003](#)). Conversely, innovations disseminate over time and space ([Berger, 2001](#)), a process known as *diffusion* ([Rogers, 2003](#)). According to [Rogers \(2003\)](#), the spread and diffusion of innovation is a temporal process during which a novel product is progressively accepted in the target market, among potential customers, and in society at large.

The diffusion of innovation is contingent upon the channels of communication and the particular social system within which it is introduced. Furthermore, the timing of an innovation's adoption is also influenced by the diverse consumer behaviours observed in different contexts. It depends on the type of innovation, whether we decide on acceptance as an option, or whether the decision is collective, or even based on the authority's will (Birkner et al., 2022). Acceptance is not only influenced by community factors. Furthermore, market factors, such as competitive production costs and available financing options, can also be beneficial. In addition, supportive regulation is essential as well (Sovacool and Ratan, 2012).

Based on previous Hungarian studies, certain factors were found to influence farmers' willingness to adopt innovation, while others did not. In a 2013 survey-based study (Takács-György et al., 2013), it was found that farm size – specifically the area of cultivated land – had the most significant positive impact on the adoption of precision farming technologies. Age also played a role: middle-aged farmers (aged 40–65) were more open to innovation, while those over 65 were generally resistant. The study did not find a significant correlation between innovation adoption and either the farm's income level or the farmer's level of education.

In contrast, a more recent interview-based study conducted between 2017 and 2018 (Hamam et al., 2023), which involved 300 farms, found that education level did matter in certain contexts. Specifically, farmers with higher education were more likely to adopt climate-related innovations such as new heat- and flood-tolerant crop varieties and the use of agrometeorological data. However, no significant correlation was found between education and the use of ice and frost protection technologies. These findings suggest that the impact of education on innovation adoption may depend on the type of innovation being considered.

THE R&D BACKGROUND OF TRUNK INJECTION

The plant protection of modern agriculture is traditionally based on foliar spraying. This is a widely used, well-known and highly developed technology, but it also has disadvantages. In certain weather conditions (wind, rain), foliar spraying cannot be applied, and it has further limitations regarding the timing of application even under good weather conditions to reduce the risk of pesticides to pollinators. In addition, spraying is disadvantageous because application waste and efficiency of pesticides also decreases by the height of trees (Bock et al., 2015; Fox et al., 2008). The technology has a large ecological footprint (ecotoxicity), uses a lot of chemicals, which need to be reduced to reach our sustainability goals (European Green Deal, 2023). New diseases appear from time to time [Dutch elm disease (Postma and Goossen-van de Geijn, 2016), citrus greening disease (Li and Nangong, 2022)], which are difficult to fight against, but require chemical intervention. This is how the demand for alternative plant protection technologies rises, the process is called market demand pull effect (Török et al., 2019).

The injection of plant trunks as an alternative plant protection method goes back to earlier traditions, but it has not been widely used so far, the R&D is still ongoing. The first written records are from the 12th century. We find more information about the experiments of Leonardo da Vinci, who developed poisonous apple by injecting arsenic. These first attempts took place in even less scientific conditions, then later in the 19–20th century, more and more studies began to experiment with injection. Between 1990 and 2000, research and development got a new boost, but it was always a disputed technology due to the health of the tree, the effectiveness

of the process, the chemical agents and equipments used, and the aesthetic harm (Li and Nangong, 2022; Berger and Laurent, 2019).

With the currently available technology, injection requires a lot of time and human labor, overall, it is an expensive technology. For quick treatment of large farms, spraying is still the better choice. The injection causes a wound on the plant, that is a potential pathway for the entry of plant pathogens. The wound might also cause side effects or complications like trunk splitting, twisting growth, sap bleeding. Furthermore, the wound of drill ruins the appearance of an ornamental plant (Darrieutott and Lecomte, 2007; Perry et al., 1991). These disadvantages can of course be reduced or even eliminated with the progress of R&D.

On the other side, the accumulated knowledge about trunk injection in the scientific literature covers treatments of at least 6 invasive insects and 20 pathogens (the latter includes fungal, fungal-like, bacterial and phytoplasma-like pathogens). Information about testing and using trunk injection is available for common host plant species such as apple, pear, palm, citrus, horse-chestnut, etc. (Li and Nangong, 2022). Adoption of technology is not the same because each countries have different regulations and legislation, and it also matters if the treated plants are ornamental plants or fruits that we eat.

Tree trunk or stem injection works with the same principle as human or animal injection. By injecting the used substance (medicine, pesticide) under the outer surface, the internal circulatory system transports it everywhere inside the body (plant). This ensures good uptake and reduces wastage. Due to its economy and accuracy, it is considered a precision farming technology. Many different tools and equipment have been developed for its application. Due to the different entering ways of the agent, the size of the injection hole (port) and drill bit there are drill-based, needle-based and cut-based technologies (Li and Nangong, 2022; Berger and Laurent, 2019).

METHODOLOGY

To meet the objectives of the study, different methodological tools were used in the research. Firstly, the current status and directions of the R&D process in Hungary were reviewed to examine the challenges the technology was facing. To understand this, *expert interviews* were conducted as a qualitative research method. Based on these results, the second step was a *questionnaire survey* to explore the perceptions of prospective users of the technology (i.e. farmers) as a quantitative tool, which are both in line with the research objectives.

Qualitative research: expert interviews

In Hungary, trunk injection is a common plant protection practice in the field of ornamental plant cultivation. An R&D project is currently ongoing, led by an industry-university research group. The project involves the implementation of trunk injection on cherry and walnut trees in an experimental plantation. The investigation is focused on two key areas: the effectiveness of the plant protection method, and the pesticide levels in the fruit. Five members of the research group were interviewed. The purpose of the interview was to understand the current status of the R&D project and to identify the *advantages and risks* of the technology. This information is particularly important for farmers as it relates to commercial implementation.

Quantitative research: questionnaire survey

A total of 80 Hungarian cherry and/or walnut farmers were surveyed in October 2024. The questionnaire compiled by the authors is based on the results of expert interviews and *collects farmers' perceptions* of trunk injection technology. Information was recorded on the type of farming activities (cherry and/or walnut), the size of the farm (0–1 ha, 1–10 ha, 10–50 ha, over 50 ha) and the age of the farmer. A presentation was given on the trunk injection plant protection method, its advantages over traditional spraying and also its risks (based on the results of expert interviews). This was followed by four main questions:

1. With regard to the trunk injection plant protection method, are you familiar with it? (yes, no)
2. Please indicate how important each advantage is using a scale of 1–4.
3. Which risks do you consider relevant/significant?
4. Could you please describe how you intend to use the trunk injection? (purchase, service, would not use)

RESULTS

Expert interviews

One of the companies within the industry-university research group has decade-long experience in trunk injection plant protection services for ornamental plants. Based on experience and research results, the advantages and risks of the technology can be clearly identified.

Based on service experiences, the advantage of the technology is that it can be used regardless of the time of day and weather conditions. During a treatment, it is necessary to use an increased amount of pesticide, but replicated applications are rarely necessary, so in the long run less pesticide is needed, overall, it can be economically rewarding. Plant protection based on traditional spraying is not effective at a certain height or in other special conditions, and a significant portion of the material is wasted.

Injection treatment of *horse-chestnut* has become routine in Hungary, mainly as a method of protection against the horse-chestnut leaf miner (*Cameraria ohridella* Deschka et Dimič, 1986). It is advantageous in special locations where spraying is problematic: inhabited areas, near hospitals or playgrounds. The treatment provides protection for 2 or even 3 years, as the decomposition of the agent is completely different to using a spraying method. As its fruit is not eaten, it is harmless to human health. Although it is an unorthodox method according to the regulations, a special permit is required from the authorities (Gyuris et al., 2021).

Its applicability to *walnut* trees is currently being studied. According to preliminary results, the method is effective against the walnut husk fly (*Rhagoletis completa* Cresson, 1929). The research is being carried out with experimental permission from the authorities. The results are promising as no pesticide residues can be detected in the nut kernel (Kiss et al., 2021, 2023). The other research direction in the case of the *cherry* plantation, controlling European cherry fruit fly (*Rhagoletis cerasi* Linnaeus, 1758) by using the injection method. The experiments also include a control group of sprayed trees (Gyuris et al., 2023).

Based on the interviews, the following advantages of trunk injection technology over traditional spraying can be identified, which are consistent with the results found in the literature:

- Lower risk to human health during application: no inhalation, no skin contact (Archer et al., 2022; Werrie et al., 2021).
- Reduced environmental impact: the pesticide is only applied to the target plant (Burkhard et al., 2015; Coslor et al., 2018).
- The pesticide can be applied regardless of the time of day (insect protection) (Archer et al., 2022; VanWoerkom et al., 2014).
- This product is effective in all weather conditions, whether windy or rainy (Archer et al., 2022; Aćimović et al., 2016).
- More cost-effective: less pesticide is needed in the long term (Burkhard et al., 2015; Coslor et al., 2018).
- More time-efficient: treatment only needs to be repeated once a year or every two years (Burkhard et al., 2015; Coslor et al., 2018).

When utilising the research results for innovation purposes, two solutions are visible: the development and *sale of injection equipment* and the *offering* of plant protection *services* to farmers.

The following risks have been identified in terms of the limitations of the technology and its commercial application:

- The price of the injection machine/device or the injection service.
- The effectiveness of the injection in terms of plant protection.
- The safety of the injection from a food safety perspective.
- New technology may be unfamiliar to farmers.
- Official approval of tree injection, availability of necessary plant protection products.
- Consequences of damage to the tree trunk caused by injection.

Based on the results outlined above, the following step in the research was to conduct a questionnaire survey of potential users (farmers) to examine their perceptions.

Questionnaire survey

We investigated the market potential of trunk injection in a questionnaire survey of walnut and cherry farmers. The results are based on responses from a total of 80 farmers (32 cherry, 26 walnut, 22 both). The reason for choosing these two crops is that research is currently underway on these plant species, so the market launch of the technology is expected in these crops first. Among the respondents, 45 farmers cultivate the relevant crops on an area of less than 1 *ha*, 22 between 1 and 10 *ha*, 10 between 10 and 50 *ha* and 3 over 50 *ha*. In the presentation of the results, farmers with less than 1 *ha* are called *backyard* farmers and those with more than 1 *ha* are called *industrial* farmers. Divided by age, 30 farmers were under 45 years, 33 between 45 and 65 years and 17 over 65 years participated in the research.

The examined sample was almost equally divided in terms of whether they had heard of trunk injection technology before (51% yes, 49% no). By age, it can be established that younger farmers (under 45) were more informed (60% yes). The awareness of the technology is not

influenced by the crop produced, but by the size of the cultivated area: the majority of backyard farmers (62% no, 38% yes) were not familiar with this plant protection method, while industrial farmers were much more familiar (32% no, 68% yes).

The respondents had to choose on a 1–4 scale how important they consider some of the advantages of trunk injection (Table 1). Based on the answers, the most important advantage of plant protection innovation is that it exerts its effect *regardless of weather conditions* (wind, rain). These answers should be considered by the marketing strategy when entering the market. Although the recognition of the technology is higher among younger people, its advantages are valued more by the older age group.

From the point of view of market entry, it is crucial to know which aspects and risks are considered most important by potential users (Table 2). According to the results, the *price* of using the technology (purchase of equipment or service fee) is a sensitive issue. Farmers are least interested in the question of the consumability of the fruit (food safety).

In relation to the future use, more than half of the respondents (55%) would buy their own device, a significant part would use it as a service (38%), and only an extremely small part would reject the technology (8%). In this regard, there is no significant difference according to farm size or age.

Table 1. Most important advantages of trunk injection

Advantages of the trunk injection technology	Answers for <i>very important</i>
Effective regardless of the weather (wind, rain)	54%
More cost-effective (less pesticides are needed in the long term)	51%
More time-saving (it is enough to repeat the treatment every year or two)	49%
Less impact on the environment (only the plant to be treated gets the pesticide)	46%
Lower risk to human health at application (it is not inhaled, it does not contact with the skin)	45%
The pesticide can be applied regardless of the time of day (bee protection)	44%

Source: own results.

Table 2. Significant risks of trunk injection

Risks of the trunk injection technology	Answers for <i>significant risk</i>
The price of the injection machine/device or the injection service	58%
Official authority permits for trunk injection, availability of necessary pesticides	50%
Plant protection effectiveness of injection	39%
A new, unknown technology for me	29%
Consequences of damage caused to the tree trunk by injection	29%
Safety of injection from a food safety point of view	24%

Source: own results.

DISCUSSION

Based on the results, the trunk injection technology may have real innovation potential. A SWOT analysis (Table 3) helps to understand the 1) the technological innovation’s challenges and 2) commercialisation perspectives.

Among the internal factors, the *strength* of the technology is lower ecotoxicity, since the agent used only gets into the tree, which reduces the environmental impact. It can be a solution in extraordinary conditions where it is not possible or unsafe to spray. The method has serious historical traditions and is already used routinely in several places (Li and Nangong, 2022; Berger and Laurent, 2019). According to the current state of the research, the concept has been proven. Preliminary results are promising about the bee protection and food safety perspective. It is expected that the active substance concentration measured in the edible part of the fruit should not be more than the maximum residue level (MRL) prescribed by the European Food Safety Authority (EC No 396/2005).

R&D in agriculture is extremely complex and time-consuming, which means *weakness*. The protective effect of the used agent, as well as the concentration values, must be examined for many years. Each plant species and agent must be separately tested, because the degradation time is different: for example, one can be used in cherries, but not in walnuts. Nowadays the treatment for horse-chestnuts is routine, but in general we can say that it is a less well-known or widespread method in Hungary and Europe. The strongest limitation of current technology is that it is not automated, but there are ongoing development directions (Li and Nangong, 2022; Berger and Laurent, 2019). This requires additional R&D activity, but until then it is now a very time-consuming and human labor-intensive procedure, so it cannot be used on large farms (industrial size).

Our sustainability goals mean *opportunities* in external factors. To deal with the effects of climate change, the European regulation trends bring increasingly strict plant protection requirements. This could force farmers to use alternative technologies in the future that can reduce the amount of pesticides. There are some other external boosters for innovation in agriculture: such as the general development of technology and the growing demand for food (Garai and Popovics, 2022). Good market potential is essential for a new innovation, which was supported by the questionnaire research. On a positive note, the overwhelming majority of Hungarian

Table 3. SWOT analysis of trunk injection technology

	Strengths	Weaknesses
Internal	Lower ecotoxicity Useable by extraordinary conditions Research history, traditions Promising research results	Complex and time-consuming R&D Not widespread technology Usability at current technology level
	Opportunities	Threats
External	Sustainability goals Market potential	Limitation of pesticides Innovation adaptation ability of agriculture Dependence on regulations

Source: own results.

farmers participating in the study are open to adopting this new technology, whether through purchase or service. An open attitude towards innovation is one of the most important factors in the diffusion of technology.

There is currently no pesticide developed specifically for this technology, which causes *threat*. This requires additional R&D time, resources, investment and mostly supportive regulation. External factors such as the ageing farmer population, the concentrating farm structure and the education level can negatively affect the ability to adopt innovations in agriculture (Hamam et al., 2023; Takács-György et al., 2013; Vágány, 2023). In general, the development and spread of technology is strongly depends on plant protection regulations. Supportive changes can be achieved by new scientific results that prove the technology's safety and effectiveness. The opposite effect is that the R&D phase is limited by strict administration. Other parts of the world with less strict regulations can speed up R&D activity.

The research demonstrated that even technologies with a long history can encounter significant innovation challenges during their development. However, innovation in agriculture is essential to achieving our sustainability goals. The new results obtained may be useful to the R&D research group and investors, on the basis of which market exploitation can be successfully prepared.

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