Direct Injection Spraying Technologies: State of the Art and Possibility of Adoption in Developing Countries

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Abstract

Direct Injection Spraying (DIS) consists on injecting chemical and carrier water online. This technology is technically appreciated as a clean method to reduce operator exposure and leftover chemical mixtures. However, DIS performance depends on lag transport and system reactivity to speed up chemical concentration process change, on chemical mixing quality in the spray line, and on cleaning of circuit processing concentrated chemical. This review gives an overview on development of direct injection spraying as a variable rate technology that has been impacted evolution of the precision agriculture during the three last decades. DIS performances are related to reduction of lag transport which has been studied by many researchers using chemical injection close to spraying boom or at the nozzle body. The DIS reactivity has been improved with reference to performance of mixing and cleaning process. From the technical and economical point of view, adoption of DIS technology is kept reserved to developed countries. An effort could be done to promote the technology adoption in developing countries by taking into account possibility of simplifying this DIS e technology and proposing cost effective DIS designs to be affordable and adoptable in the context of small scale farming.

Key words: Pesticide, direct, injection, spraying, technology, performance, adoption.

Technologies d'Application des Pesticides par Injection Direct: Etat de l'Art et Possibilité d'Adoption dans les Pays en Développement

Résumé

Un système de pulvérisation par injection directe (DIS) consiste à injecter en ligne un produit chimique liquide dans de l'eau jouant le rôle d'un liquide porteur. Cette technologie est techniquement appréciée comme méthode propre pour réduire l'exposition de l'opérateur et les restes des bouillies chimiques. Cependant, les performances des systèmes DIS dépendent du délai de transport des concentrations chimiques, de la réactivité du système permettant d'accélérer le processus de changement des concentrations chimiques et de la conception du système de pulvérisation pour assurer un bon mélange de produit chimique en cours de transport sur la ligne hydraulique de pulvérisation. Le nettoyage du circuit hydraulique de dosage et d'injection des produits chimiques concentrés constitue aussi un critère de jugement de performance et de chance d'adoption des systèmes DIS. La réduction de délai du transport a été étudiée par de nombreux chercheurs en utilisant l'injection du concentré chimique à proximité de la rampe de pulvérisation ou au niveau des porte-buses, mais une telle amélioration ne peut être réalisée sans affecter la performance du processus de mélange et le nettoyage du circuit hydraulique. De point de vue technico-économique, la diffusion de la technologie DIS reste encore réservée aux pays développés. Tout tentative visant la promotion de l'adoption des technologies DIS dans les pays en développement ne pourrait se faire sans simplification des systèmes DIS proposés. Il est possible de proposer une technologie DIS à prix abordable, potentiellement adaptée pour le contexte des petites et moyennes exploitations agricoles.

Mots clés: Pesticide, directe, injection, pulvérisation, technologie, performance, adoption.

تكنولوجيا الرش بالحقن المباشر: مستوى التقدم الفني الحاصل وإمكانية التبني في البلدان النامية

العساوي عبدالله، فريديريك لوبو، كريم هومي، البحير لحسين و بحري عبدالجبار

ملخص:

يتضمن نظام الرش بالحقن المباشر حقن مادة كيميائية سائلة في الماء لتكوين سائل ناقل. تم تقدير هذه التقنية تقنيًا كطريقة نظيفة لتقليل تعرض المشغل و تقليل بقايا الخلط الكيميائي. ومع ذلك ، فإن مردودية أنظمة الرش بالحقن المباشر تعتمد على تقليل وقت نقل التركيزات الكيميائية ، وتفاعل النظام لتسريع عملية تغيير التركيزات الكيميائية ، وتصميم نظام الرش لضمان الخلط المناسب للمادة الكيميائية خلال عملية نقل السائل على خط الرش الهيدروليكي. يعد تنظيف الدائرة الهيدروليكية لنظام حقن المواد الكيميائية المركزة معيارًا للحكم على أداء واحتمالية اعتماد أنظمة الرش بالحقن المباشر . تمت دراسة تقليل وقت النقل من قبل العديد من الباحثين باستخدام حقن المواد الكيميائية المركزة بالقرب من قضيب الرش أو عند حوامل الفوهة، ولكن لا يمكن تحقيق هذا التحسن دون التأثير على أداء عملية خلط وتنظيف الدائرة الهيدروليكية. من وجهة النظر الفنية والاقتصادية، لا يزال نشر تكنولوجيا الرش بالحقن المباشر محجوزًا على البلدان المتقدمة. ولا يمكن القيام بأي محاولة لتشجيع اعتماد تكنولوجيات الرش بالحقن المباشر في البلدان النامية دون تبسيط أنظمة الرش بالحقن المباشر المقترحة. ومع ذلك من الممكن توفير تقنية الرش بالحقن المباشر ميسورة التكلفة، والتي قد تكون مناسبة لسياق الزراعات الصغيرة في البلدان النامية.

الكلمات المفتاحية: سائل كيميائي، نظام الرش ، حقن ، مباشر ، تكنولوجيا ، أداء الرش ، اعتماد.

Introduction

Intensive farming is fully linked to activities causing chemical pollution, soil and biodiversity degradation. Rational application of agricultural inputs trough use of variable rate (VRT) technologies contributes to preserve natural resources and increase the sustainability of agricultural system not only in developed countries but also in developing countries.

Direct injection spraying (DIS) is a variable rate application technology consisting on processing chemical concentration on the go and proportionally to the operating ground speed. Evolution of this variable rate technology has been done within the context of precision agriculture (PA) development to apply modulated agricultural input. In fact, the digitalization progress of electronic and process control devices played a primordial role for implementing cost-effectively spraying equipments equipped with controllers, sensors and actuators to improve spraying technology performance for precise chemical application.

Since 1990s, different DIS technologies have been assessed to apply variable chemical rate online. It consists on injecting a chemical formulation of an active ingredient in an online constant or variable carrier flow rate (Koo et al., 1987; Tompkins et al, 1990; Sudduth et al., 1995; Qui et al, 1998; Zhu et al, 1998; Anglund and Ayers, 2003; Hloben (2007); Lammers et al. (2010), El Aissaoui (2011); Elamouti et al. (2014); Felizardo et al. (2016), Luck et al. (2019) , Zhang et al. (2019)). In general, VRT technologies have been gradually adopted in the last decades. However, its spreading kept only reserved to countries having large areas under cultivation. In North America, there is a great interest for adoption of PA and VRT due to impact of intensive farming and awareness about the environmental issues. However, the adoption in developing countries is kept very low.

This work aims to review the research progress on DIS technologies within the trend of precision farming development. This manuscript is organized to give a global overview on different aspects of DIS, such as concepts, hydraulic designs, process control, systems performance, safety requirements, advantages and drawbacks, technology progress and commerce state. After that, an attempt for developing low cost electric DIS technology adapted for small scale farming is discussed as example for promotion in the context of developing countries.

Concept of variable rate application and errors

Technical application rate control

Control of chemical application rate in a conventional sprayer is based on the parameters of nozzle flow rate (q_n in L/min), number of operating nozzles (n), chemical concentration in the tank solution (Cm), boom working width (W_b in m) and operating speed V (km/h). It consists on applying chemical at a given technical application rate as shown in Eq. 1:

$$TAR(L/ha) = \frac{600 * n * q_n * Cm}{V * W_b} \qquad (Eq.1)$$

Achievement of a constant application rate is independent of operating speed and mainly based on one of the three methods of application rate control:

1. Flow control of the tank mixture (conventional method). The active ingredient is pre-mixed with the carrier in the tank; hence, the chemical concentration in the spray mixture during application is constant and the flow kept constant or varied proportionally to working speed (Fig 1A).

2. Chemical flow based on a constant carrier flow.

3. Combination of chemical and carrier flow control (total flow control).

The first method is based on applying chemical mixture at a constant or variable operating hydraulic pressure in accordance with constant or variable ground speed. However, the second and third methods (Fig.1B) are based on metering and injecting chemical active ingredient proportionally to a variable working speed (Koo and Sumner, 1998). The injection point location has a direct effect on reactivity of the injection system to change concentration according to speed variation. The system response time can be improved as lag transport is reduced by injecting closely to tip nozzles. However, the online mixing of chemical with carrier is affected if the active ingredient is injected at the upstream position of the carrier pump, or at the boom section level or at the tip nozzle level.

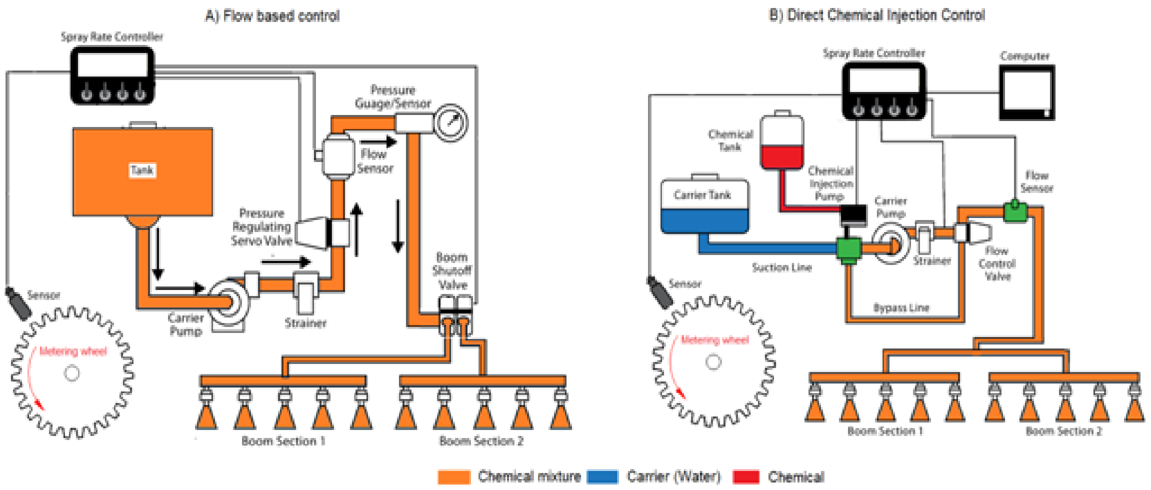

Figure 1: Chemical application rate control used in agricultural spraying: Flow based control (A) of tank mixture versus direct chemical injection control (B)

Application rate error

Application error in a spraying operation is computed as average value or percentage of application exceeding a tolerable application rate within an acceptable range of 5% (USDA, 1989). Evaluation of current application technology leads to quantify error in chemical application and to approach static and dynamic performances of spraying systems for different working speed conditions in agricultural field.
Miller and Smith (1992) evaluated direct boom injection system inaccuracy due to time delays caused by speed change. They assumed application of a chemical at a TAR of reference with an actual TAR (t) applied at any time t. The error associated with the application is described by Eq.2. It can be reduced to Eq.3 for describing a fractional error due to application at any time t. The Eq.3 shows the effect of the ground speed to influence application rate error.

$$e = \frac{TAR(t) - TAR}{TAR} \qquad (Eq.2)$$

$$e(t) = \frac{V(t_c)}{V(t)} - 1 \qquad (Eq.3)$$

Effect of Time delay on application rate error

Concentration is constant over time when applying chemical mixture by conventional sprayer. A premixed concentration in the sprayer tank is adapted to an intended ground speed that needs to be maintained constant all time. Error is solely based upon deviation from the intended ground speed. But in the case of direct boom injection system, there is a complication as the concentration process change depends on time delay due to transport of chemical between the point of injection and the point of application. Furthermore, the time delay associated with each nozzle increases with boom width. The farther a nozzle is from the point of application, the

longer is the time delay. Thus, when considering the concentration of a chemical at a given nozzle, the ground speed upon which the concentration is based is not the current time, it is the current time less the time delay for the nozzle (Tomkins et al., 1988; Budwig et al., 1988).

Lateral application error in DIS boom

Miller and Smith (1992) studied the effect of time delay on application error and also the error propagation along DIS boom. They evaluated the time response of 10 meters' boom (20 nozzles spaced of 0.5 m) of 1 inch diameter and having a central chemical injection situated at 0.3 m in upstream point to feed two half boom in parallel layout. They found that for a flow rate of 1.5 L/min per nozzle the time delay varied from 0.8 s for nozzle 1 to 29.7 s for nozzle 10. For studying the error behaviour along the spraying boom, the authors simulated a sinusoidal variable ground speed to examine time delay and effect of speed change on application accuracy. A direct boom injection system is assumed to work under a constant speed solicitation for 30 s before shifting to sinusoidal speed form as follow:

$$v(t) = v_0 \sin(2\pi A t / T) \qquad (Eq.4)$$

Where v_0, A, t, and T are the reference speed of 8 km/h, the fractional speed variation of 0.05, time and periodic oscillation of 10 s, respectively.
The sinusoidal function form is used for representing the minor speed variation that can potentially occur around a target speed value due to tire slippage or irregular field working conditions. The results (Miller and Smith, 1992) showed that for a typical direct boom injection system, a small error in ground speed can be amplified into a larger application error. In fact, application errors in the nozzles 3, 4, 5 and 8 exceeded the acceptable range limited at 5%. The errors amplification is due to ground speed variation in cyclic discordance added to concentration change along the boom due to a consistent delay response. The authors found also that the minimum error occurred in nozzles 9 and 10 having time delays of 19.5 and 29.7 s, respectively. These time delays present a cyclic accordance in phase with the 10 s period in the speed oscillation. However, the performance was practically poor for nozzles having time delays occurrence in mid-cycle. In similar study, Koo et al. (1987) quantified application error of a direct boom injection of 12 nozzles due to transient response to find that a periodic speed change of 9 ±1.6 km/h at 10 s can induce a misapplication of 10% and a mistreated area of 24%. Application error of a direct injection spraying boom is characterized not only by its nature but also by its magnitude to study different situations of speed change that can occur in an agricultural field. Design of direct injection boom system can improve DIS performance if the time delay is low for precise chemical application. In fact, direct injection spraying boom can be of superior performance if the hydraulic design and the controller design are yielded to improve the spraying system reactivity for different working speed solicitations.

Control of variable rate application

To vary application rate, there are mainly two techniques used to change system pressure or flow rate. The control of the operating pressure or flow rate can be done using two ways or three ways valves or by varying the rotating speed of the electrically driven pumps using pulse width modulation (PWM) technique or by controlling the nozzles flow rate using PWM actuated valves.

Hydrostatic flow rate control by pressure setting

Variation of spraying system pressure is based on the principle of the square root model governing hydraulic nozzle flow. For an operating pressure range of a hydraulic nozzle, the flow rate (Qn) is controlled in a narrow range. To double the nozzle flow rate, a four time increase of pressure (P) is required according to the nozzle orifice model as follow:

$$Qn = k_n \sqrt{P} \qquad (Eq.5)$$

Where K_n is the discharge coefficient.

The operating pressure range for conventional nozzles is narrow as the drift potential is higher by increasing operating pressure (Frost, 1990; Qiu et al., 1998). This technique require use of nozzles operating at an extended pressure range (example of Teejet^{TM} XR). These nozzles provide a consistent spray pattern within a pressure range of 1 to 4 bars. However, conserving spraying quality and volume distribution pattern is a limiting factor for the conventional hydraulic nozzles as the pressure drops below or goes above the specified level to cause drift as a consequence of coarse or small generated droplets. The range of applied rate to spread out with a given size of conventional nozzle size by changing the liquid pressure in a recommended range is limited to ±25 % of the nominal output of 1.25 times. The control of the sprayer output for a wide range of application rates can be improved by using a twin-fluid nozzle that can carry out a flow rate in a range of 3 times (Paice et al., 2001).

Otherwise, the development of variable rate nozzle can adequately solve the problem of working in wide range of pressure-flow rate. The use of variable rate nozzle improves coverage and avoids drift (Bui, 2005). In fact, the variable orifice allows a variable flow rate within a range of 10 times without affecting droplet size. The performance test of Varitarget nozzles showed a better coverage at higher pressure in comparison to conventional nozzles (Daggupati, 2007). However, its adoption is limited by its affordability due to its price ten times higher.
The commercialised designs of DISs are technically based on controlling flow rate output using hydrostatic pressure feedback and bypass flow to the carrier and/or to the chemical tanks for processing variable applied rate. This method is energy consuming as there is a return flow to the tanks (Hardi, 1997; Koo and Sumner, 1998; Hloben, 2007; John Deere, 2011).

Hydrodynamic flow rate control by PWM technique

Hydrodynamic control of injection and carrier pumps can be performed using PWM actuators with reference to their operating speeds and/or voltage. Practically, there are two ways to control flow rate with a PWM technique:

- Use of PWM actuated solenoid valves to control flow rate of individual nozzles.
- Use of PWM to control the pump rotational speed for changing the operating pressure and flow rate conditions.

Use hydrodynamic control and injection in suction side with possibility of displacement of electrical carrier pump close to centre of boom line are important options to improve energy and dynamic performances of electric DIS (ElAissaoui, 2016). The options are also economically interesting to build up affordable DIS for use in small scale farming. In fact, Use of PWM method is of importance to reduce energy consumption as the bypass flow is avoided. The energy efficiency and cost of DIS can be reduced using hydrodynamic control as the pumps actuation is performed without use of back flow control and bypass regulator valves.

Pierce and Ayers (2001) tested the accuracy of PWM for field sprayer equipped with the nozzles pulsing at duty cycle settings of 25 to 100%. They found that nozzle pulsation had no effect on the spray pattern along the boom but the longitudinal uniformity varied with sprayer working speed and suggested faster actuation frequencies for short duty cycles to obtain a finer pulse resolution for a more uniform spray pattern along the working travel line (Pierce et al., 2001). Han et al. (2001) modified a commercial sprayer with 25 tip nozzles for variable rate application. This sprayer was equipped with pulse-width modulation solenoids, a pressure controller and a nozzle control system interfaced to computer. They found that the flow rate change due to inaccuracy of the pressure controller ranged from 0.5 to 2.5%. They also found that the flow rate control errors for valves ranged from -15 to 12% when a single flow rate calibration curve was used.

Process control strategies for variable rate application

Constant carrier flow control (CCFC)

The principle of constant carrier flow control is based on varying chemical concentration in carrier flow proportionally to the working speed and maintenance of a constant total flow rate (Fig.2a). This concept is known as the "Injection Metering" or the "Direct Injection" systems (Koo and Sumner 1998). The chemical active ingredient is metered, injected, and mixed online into diluent flow which kept constant. The CCFC method offers the possibility to keep nozzle flow rate steadily unchanged without influence on spray pattern. However, the speed increase gives a reduced coverage of the target. Therefore, the biological efficacy of chemical may be affected as a consequence of a decreasing number of droplets impacts per unit area (Hughes and Frost, 1985).

Total flow control (TFC)

TFC method is mainly based on varying simultaneously the chemical injection flow rate and the carrier flow rate proportionally to a working speed (Fig. 2b). The application rate is kept constant by varying nozzles' flow rate through adjustment of its operating pressure.

Koo and Sumner (1998) developed a DIS based on TFC. The system hydraulic circuit was constructed with 25 mm internal diameter (I.D) hoses for inlet and outlet to the main pump, 20 mm I.D. PVC pipes for main and bypass lines, and16 mm I.D. hoses for a 6 meters' boom of ten nozzles (Teejet XR8002). The response time of this flow control system averaged 8.5 s at an absolute steady state error of 0.8 % of flow rate. The average response time for the injection rate was 0.53 s and the coefficient of variation (CV) of concentration was 3.2 %.

Steward and Humburg (2000) evaluated the performance of Raven SCS-700 chemical injection system with carrier flow control by modelling chemical and carrier control sub-systems. They found as results that chemical injection with carrier control resulted in less application error compared to chemical injection without carrier control. The carrier control minimizes the concentration variations caused by dynamic response differences between the two sub-systems and reduces the effect of transport delays. However, TFC cannot provide consistent spray characteristics over a wide flow range without use of variable flow nozzles (Koo and Kuhlman, 1992).

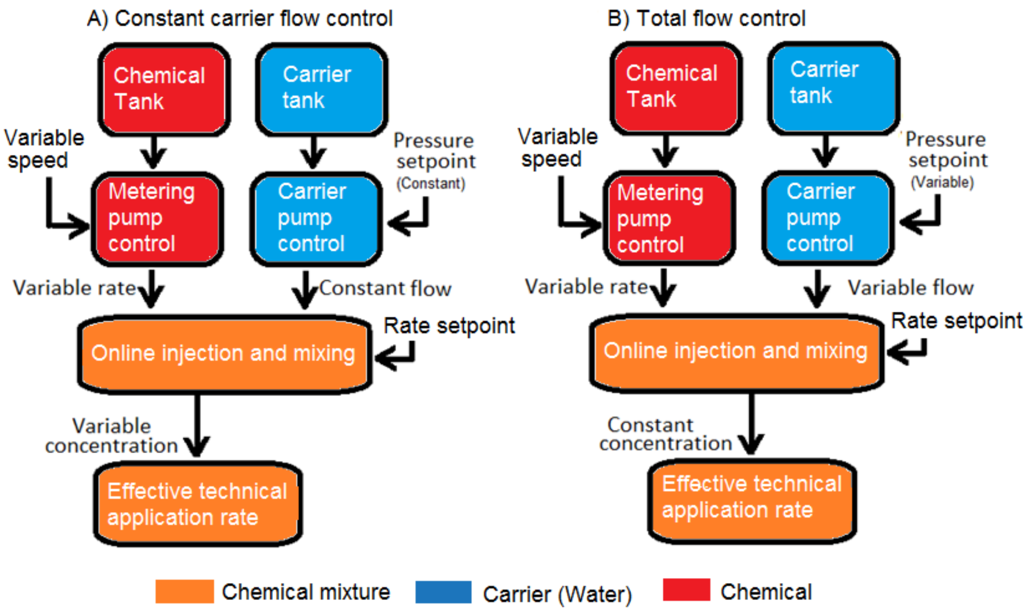

Figure 2: Control strategies for varying application rate in DIS: a) Constant carrier flow control b) Total flow control

Hydraulic designs and performance of DIS

DIS systems are classified into central direct injection systems (CDIS), boom section direct injection systems (BDIS) and nozzle direct injection systems (NDIS) (Landers, 1999; Lammers et al, 2010).

Central Direct Injection System (CDIS)

In the CDIS, chemical can be injected into the system at upstream or downstream point of the main sprayer pump and prior to the boom sections (Fig. 3). The CDIS can potentially provide a slow dynamic response as a consistent lag time can occur to change the chemical concentration at the nozzle level relatively to corresponding change at the delivery points (Walker and Bansal 1999). Although, a multitude of CDIS have been developed, the adoption of this technology is limited by the performance of such system DIS that is not satisfactory because of the lag transport between the injection point and the tip nozzle causing problem of a delay in response time. This time delay can potentially be more than 20 s, causing application error of more than 100 m in the field (Koo et al., 1987; Tompkins et al, 1990; Sudduth et al., 1995; Qui et al, 1998; Zhu et al, 1998; Anglund and Ayers, 2003; Hloben, 2007).

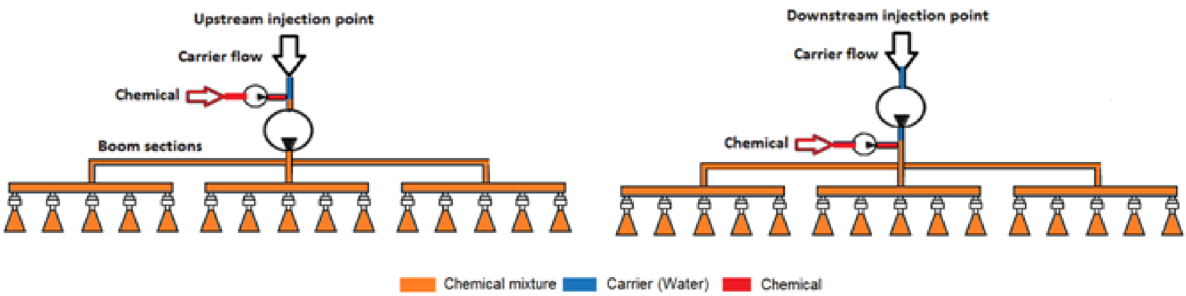

Figure 3: Central Direct Injection System designs: Upstream and downstream injection points

Boom Direct injection system (BDIS)

The injection of chemical into the carrier can be done in downstream position to distributor serving solution to different boom sections and at the centre of each boom section carrying solution to different nozzles (Fig. 4). In comparison with CDIS, there is a reduced distance between injection point and nozzle and consequently the response time is also reduced.

Hloben (2007) studied a BDIS and found a system response times less than 4 s, resulting in an application error of less than 20 m in the field. BDIS can have slow or fast responses for real-time controlled application depending on the sprayer operating speed that varies from 1 to 4 m/s.

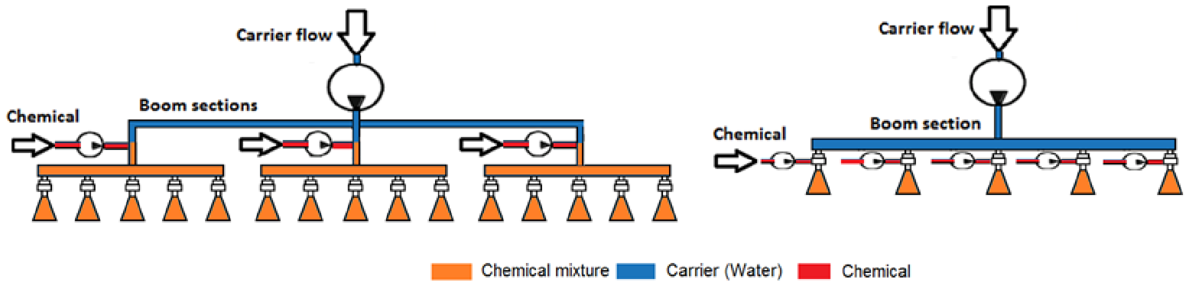

Figure 4: Designs of direct chemical injection at boom section and tip nozzle levels

Nozzle Direct Injection System (NDIS)

Direct nozzle injection reduces lag transport and provides less response time in comparison to that of the boom section injection (Fig.4). However, problems of mixture homogeneity can arise when using direct nozzle injection (Zhu et al., 1998). In the case of boom injection systems, the mixing quality is usually not affected as a pesticide has sufficient time to be mixed with the carrier before being sprayed throughout sprayer's nozzles. For direct nozzle injection the time for mixing is reduced (Rockwell and Ayers, 1996). NDIS has a disadvantage of high cost needed for implementation chemical delivering equipment for each nozzle.
Giles and Brock (2008) used air induction (AI) nozzle with an embedded venturi for implementing NDIS. They used venturi vacuum to induce injection liquid flow. They stated that volumetric concentration of injected fluid in the nozzle could be controlled over 3% to 20% through use of metering orifice plates in the inlet lines. The results established the feasibility of AI nozzle for passive injection (Giles and Brock, 2008). El Aissaoui et al. (2018) used also a venturi injector and standardized orifices to optimally setting and controlling applied chemical injection rates for a large range of active ingredient rates of plant protection products. This injector was used as low cost technology to solve problem of residual volume of stationary spraying systems used in greenhouse vegetal crop productions.

Luck et al. (2019) tested a NDIS prototype based on a high-pressure direct nozzle injection system with variable-flow carrier control to improve chemical mixing and response times. They carried out an application rate of 4.68 L ha-1 with a typical varying velocity from 4.0 to 7.1 m s-1 and found that the nozzle respond in 0.5 s and the steady-state errors ranged from 2.5% to 7.5% to deliver chemical concentrations with a selected chemical to carrier ratio of 0.036.

Advantages and drawbacks of DIS designs

Lammers and Vondrika (2010) compared DIS systems on the basis of their characteristics such as application flexibility, response time, mixing quality and system cost. The improvement of application accuracy by reducing the response time of a direct injection system is not achieved without affecting the time needed for the mixing preparation.

Table 1 shows this controversy by considering response time and mixing quality performances criteria. The comparison between CDIS, BDIS and NDIS shows that the cleaning of residual pesticides is easy in CDIS due to low dead volume of hydraulic line transporting concentrated formulations to injection points. However, cleaning of BDIS and NDIS can be difficult according to importance of the dead volume. Furthermore, the system cost is of great importance for the technology spreading. The technical complexity of DIS leads directly to higher costs and limits its adoption.

Advantages of VRT cannot be fully taken without use of efficient DIS with accurate dose controller, high response to speed variation and having ability to operate over a wide range of delivered dose with variable concentration of mixtures (Miller et al., 1997). Improvement of DIS Performance consists on improving instantaneous control of the spray application process as the chemical can be added online and applied to satisfy phytotechnic requirements. However, DIS satisfy also requirements of safety operator and environment protection as the principal sprayer tank keeps clean of pesticides and management of remaining tank mixture can be avoided. The worker exposure to chemicals and leftover of spray mixture can be consistently reduced. It is also possible to recuperate chemical for reuse and to inject different chemicals from separate containers in a parallel scheme (Tompkins et al, 1990; Zhu et al., 1998). Main drawbacks of DIS are due to handling risk of concentrate formulations and to difficulty of injecting flowable and dry formulations. Use of premixing tank is used to prepare intermediate concentration of incompatible formulations.

Table 1: Performance of spraying systems (adapted from Lammers et al., 2010).

	Conventional sprayers	Central direct injection	Boom direct injection	Nozzle direct injection
Application flexibility	--*	0	+	++
Response time	++	--	0	++
Mixing quality	++	++	+	0
Cleanability	--	++	-	--
System cost	++	0	-	--

*Impact factor: ++ very positive; + positive; 0 neutral; - negative; -- very negative

Performance requirements of DIS

Deficiency of DISs is mainly due to transient errors of chemical application, spray coverage variation related to changes in operating speed and potential variability of chemical deposition due to inadequate mixing process. According to Luck et al. (2012), the two most common performance factors related to direct injection systems are lag time and mixing uniformity of the chemical with the carrier prior to discharge. After chemical injection prior to or into a spray boom, potential delay time causes change in concentration to become fully established at spray nozzle level. Lag time results in a transient error of application rate (Koo et al., 1987; Budwig et al., 1988; Tompkins et al., 1990; Hloben, 2007; Lammers et al., 2010).

Concentration process change and lag transport

Lag transport is the most important indicator for evaluating reactivity of DIS to change concentration equilibrium of applied mixture when working spraying conditions of speed or rate application are changed. The reactivity performance of DIS system depends not only on hydraulic hardware design but also on process control system dynamic to change concentration of applied chemical and volume rates (through formulation injection flow rate and carrier flow rate). The performance depends on shortness of time to fasten establishment of chemical concentration at the nozzles level. Zhu and al. (1998) evaluated lag times at boom section of an inline injection sprayer system. They measured time period between a change in chemical injection rate and the new chemical rate reaching nozzles at the boom. They investigated factors influencing lag time (number of active nozzles, boom size, travel speed changes, and pesticide viscosity) to found its decreasing by reducing the boom diameter. This reduction was not substantial when the number of active nozzles on the boom is decreased. Effect of simulated pesticide viscosity on lag time was also low (Zhu et al.; 1998).

Alamouti et al. (2014) installed a control system on a field sprayer to develop a map-based variable-rate direct injection sprayer. They used an electrical conductivity (EC) sensor to evaluate the system response time. They found for different working pressures (3, 4 and 5 bar), travelling speeds (3, 6 and 9 km h^{-1}) and spraying concentration change rates (2, 3 and 4 L ha^{-1}) a significant effect on the response time to vary between 25.8, 22.8 and 17.9 s respectively.
Felizardo et al. (2016) developed mathematical models for processing chemical direct injection to perform efficient control strategies for carrier-chemical mix. The models were based on the physical parameters of the hydraulic, electrical and mechanical components, fluid equations and experimental calibration in order to adequately assist the design and errors prediction of variable rate application systems. The experimental tests showed a best fitting with models in terms of time constant and transport delay parameters for carrier and chemical mixing process. The process responses showed varying time constants and delays from 7.5 to 23.04 s.

Cai et al. (2016) developed a prototype of a direct nozzle injection system (DNIS) to reduce chemical concentration transport lag of a variable rate applicator for site specific use. They used a rapid-reacting solenoid valve (RRV) for injecting chemicals using variable PWM at 100 Hz, the test results indicated that the set-point chemical flow rate could be achieved within less than 4 s, and the output stability was improved compared to the case without control strategy.

Table 2 summarizes the works done by several authors that evaluated performances of direct injection systems. The table shows a lag time ranging from 1 s for the case of DNIS to 80 s for the case of CDIS according to systems configurations of injection point and type based spraying.

Table 2: Recapitulative of dynamic test performance of different DIS (several authors)

Year	Authors/ Institute	DIS type	Trademarks and Specifications	Reaction time (s) and Misapplication (linear m or %)	Type based spraying
2019	Luck et al.	NDIS	Research prototype (nozzle injection)	Less than 1s at speed from 4 to 7 m/s, Error from 2.5 to 7.5 %, Chemical to carrier ratio of 3.6%	Map-based
2019	Zhang et al.		Prototype of premixing in-line injection system (upstream injection)	Pump error less than 5% Max mixture uniformity error of 7.6% for a chemical to carrier ratio of 1 to 2%	VRT orchard spraying
2016	Cai et al.	NDIS	Research prototype (nozzle injection)	Up to 4s	Map-based
2016	Felizardo et al.	CDIS	Research prototype (upstream injection)	7.5 to 23.04 s.	Map-based
2014	Alamouti et al.	CDIS	Research prototype (upstream injection)	25.8, 22.8 and 17.9 s @ 3, 4 and 5 bar and 3, 6 and 9 km h-1, respectively	Map-based
2012	Arvalis Institute	CDIS	SP-ID of Spray Concept (upstream injection); Sidekick-Pro (Raven) (downstream injection)	60 to 80 s vs dead volumeof hydraulic circuit; Up to 220 m (@10 km/h)	Map-based
2011	El Aissaoui et al.	CDIS	Research prototype (upstream injection)	< 3 s; Up to 2 m, (< 5%) (@3,6 km/h)	Speed based
2009	Hoogterp	CDIS	Hardi sprayer (Raven DIS)	20 s; 33 m (@6km/h) (downstream injection)	Map based
2007	Hloben	BDIS DNIS	Research prototype	- 2.8 s to 4 s (BDIS, 6 nozzles, XR80015/XR8005 at 3 bars). - 0.5 s to 1 s (DNIS, nozzles XR80015 and XR8005 at 3 bars).	Spot based
2003	Gillis et al.	CDIS	Roadside spraying with Raven-SCS750 (upstream injection)	25.5 to 128.1s (vs activenozzles number); Large error of 20%.	Site specific spraying
2005	BBA	CDIS	Teejet-LH	10 to 40 s; Up to 120 m	Speed based
2003	Anglund et al.	CDIS	Raven-SCS750	15 to 55 s; include 2.35 s of GPS response; Up to 160 m; 2,25% (controller error)	Map-based
2003	Ruixiu et al.	CDIS	Mid-Tech TASC 6300	Lag time (38,3 s), rise time (65,9 s)	Map-based
2002	Baio et al.	CDIS	Mid-Tech TASC 6600	28 s; Up to 55 m	Map-based
1998	Koo et al.	CDIS	Prototype	8,5 s; 3,2 % (of concentration error)	Speed based
1998	Zhu et al.	CDIS	Raven-SCS700	20.3 to 42.8 s	Speed based
1998	Qui et al.	CDIS	-	15 to 52.6 s; Up to 7,46 %	-
1997	Benneth et al.	DNIS	Prototype	< 1 s	Site specific spraying
1996	Rockwell et al.	DNIS	prototype based on Raven injection module	< 4 s; 5,3%	Speed based
1995	Sudduth et	CDIS	Raven-SCS750	14 to 21 s include 4 s response of	Speed

	al.		(upstream injection)	metering pump; Up to 50 m.	based
1992	Landers	CDIS	Commercial sprayers	Up to 30 s	Map based
1992	Miller et al.	CDIS	Research prototype	29,7 s	Speed based
1990	Frost	CDIS	Research prototype	4,3 s	Speed based
1990	Tompkins et al.	CDIS	Research prototype	23 to 26 s (upstream injection); 12 s (downstream injection).	Speed based
1988	Budwiget al.	CDIS	Research prototype	22 s (@8km/h); Up to 49 m	Speed based
1987	Koo et al.	CDIS	Raven-SCS700	20s; Up to 50 m	Speed based
1987	Chi et al.	CDIS	Research prototype	5 s	Speed based
1988	PAMI*	CDIS	Test report of SSCIMS**	10 to 30 s(@10km/hr); 30 to 80 m; Max error of 25%	Speed based

*Prairie and Agricultural Machinery Institute

Mixing quality requirement

Mixture homogeneity is an indicator of uniform spray deposition and distribution. Uniformity of chemical mixture and spray deposit distribution (lateral and longitudinal boom distributions) are determinant indicators for performance testing of DIS equipment. Concentration uniformity of an applied mixture depends not only on hydraulic system ability to induce turbulence flow for intensive online mixing but also on formulation characteristics of an active ingredient. The mixing process is considerably influenced by formulation type, polarity, and viscosity. In fact, viscous herbicides tend to exhibit a large drag effect and cannot be easily mixed with water carrier.

Hloben (2007) admitted a maximal admissible limit of 15% for a mixture concentration in a solution tank. Vondricka et al. (2009) limited maximum deviation from homogeneity for direct injection system at 5% in the nozzle output. They used decolourization method and sensor for mixture quality measurement and proposed installation the tip nozzle level. Mixing quality of an injected pesticide online into water carrier depends on factors of available time for solution transport, flow turbulence and design of mixing chamber.

Use of boom or nozzle injection points do not satisfy enough time to complete mixing of chemical and carrier before the nozzle discharge (Tompkins et al., 1990; Rockwell and Ayers, 1996; Zhu et al., 1998; Sumner et al. 2000). Tompkins (1990) investigated mixture uniformity in three injection systems with different injection positions: upstream and downstream of the carrier pump and in the individual nozzles. The chemical concentration variations at the nozzle were greater due to downstream injection. NDIS of chemical into the individual nozzles failed to achieve a uniform chemical concentration from nozzle to nozzle. The concentrations deviated by 19.5 to 39 % from the average concentration. Rockwell et al., (1996) similarly found a maximum coefficient of variation of 16.3% by studying a direct nozzle injection system. Installation of mixing apparatus for injection system can improve turbulence in the case of direct nozzle injection due to a momentary mixing period.

Zhu et al, (1998) studied mixture uniformity in diameters 3/8 and 1/2 inch of spraying boom sections of 5 meters length and across spray patterns. They used three water-soluble liquids (water, Prime Oil I and Prime Oil II) and one non-water-soluble liquid (Silicon Oil) of viscosities ranging from 0.9 to 97.7 mPa·s for simulating pesticides spray delivery in both diameters booms. The viscosities of tested liquids slightly influenced mean flow rate from the metering pump and the two highest simulated viscosities were difficult to mix with water that it was necessary to use a spiral mixer to maintain a uniform mixture. The variation from 770 to 15,000 of the flow Reynolds number in the nozzle supply line did not have a statistically significant effect on the mean concentration collected at the boom section nozzles. The average coefficient of variation among concentrations was 4,22% which tended to be greater for boom sections with 2 and 4 active nozzles than for sections with more than 6 active nozzles. The mixture across the spray pattern of all nozzles was uniform, even if the mixture in the boom was not. The average coefficient of variation was 1.31 %.

The uniformity variability of applied chemical along the spray path can be due also to pulsation of the metering pump or valve. Sumner et al. (2000) evaluated the effect of four spray nozzle arrangements and injector pump frequency on uniformity along the spray path using collector strings sprayed with fluorescent dye. They found that injector pump frequency and nozzle type were the significant factors affecting spray deposit uniformity differences along simulated path of crop rows. The low pump frequencies affected less the uniformity along the path for cone nozzles with large wetted areas than for fan type nozzles. The injector pump frequencies of 300 rpm resulted in string fluorescence CV less than 10% with no significant difference between CVs for pump frequencies of 1725 rpm.

Zhang et al. (2019) developed an experimental automatic premixing in-line injection system for variable-rate orchard sprayers using Arduino platform. They tested this premixing in-line injection system to find stable and accurate performance (Error less than 5%) for improving spray application efficiency with minimized tank mixture leftovers for future variable-rate sprayers.

Cleaning requirement of DIS

DIS is a promising technology for applying chemical but it cannot fulfill all benefits without having improved cleaning process and closed transfer plumbing circuit for safe management of residual concentrated chemical that can be hold in metering system after spraying operation. According to Landers (1992), the cleaning of CDIS is easy as only a small part of the piping system gets contaminated with concentrates pesticides. Rockwell and Ayers (1996) stated that DNIS disposes of long plumbing to hold concentrated pesticide chemical. However CDIS and BDIS have only short part of hydraulic circuit that can be contaminated regarding the cleanability of the three DIS.

The company Hardi (1997) proposed a DIS for “need dosage”that disposes of a cleaning system based on a directional valve for passing water from the carrier tank to the chemical tank through one or more washing nozzles. The nozzles are used in a simple manner in the field for cleaning internally the chemical tank and plumbing of the metering system. This DIS is also designed to be equipped with chemical filler

device having a graded scale for simple and safe filling and subsequent flushing of both liquid and powder-formulated preparations.

Dorpmund (2012) identified strategies for efficient cleaning of DIS including reclamation of residual concentrated pesticide from the injection pipe and rinsing of the contaminated parts of the hydraulic system. He studied the cleaning ability of DNIS in laboratory condition using a safe-to-use mixture solution of polyvinylpyrrolidone (PVP) and water as a test pesticide before cleaning. The cleaning process was divided into two steps of (1) reclamation of the simulated pesticide by pushing it back into the pesticide tank using pressurized air (pre-cleaning) and of (2) rinsing the contaminated part of the hydraulic system with water.

Evaluation of the process included variation of pre-cleaning time and air pressure as well as water inlet positions. The measurements for a 3 m test section showed that the initial concentration (30%) of the simulated pesticide in the rinsing water can be reduced by one third when extending the pre-cleaning time. Change of the water inlet position reduced also the initial concentration of the simulated pesticide in the rinsing water to be 5%. The author found that these concentrations were much higher than concentration of common sprayed solutions and need further dilution in the rinsing water to be sprayed on a crop. The author found that the tested cleaning process can be improved by including the homogenization of the contaminated rinsing water for uniformly dosing and applying it in the field after spraying operation.

Direct injection of flowable pesticide

Performance of direct injection system depends on its ability to deliver and inject a wide range of chemicals having varying physical proprieties with satisfying metering precision. Injection of flowable pesticides cannot be done by DIS without technical device for maintaining constant injected concentration. This later can be affected by non-Newtonian behavior of injected particulates in suspension. The non-Newtonian fluids cannot be perfectly processed without using continuous mixing device to maintain homogeneous injected fluid. The metering pump requires calibration for each flowable formulation depending on its physical and chemical characteristics.

Injection of dry flowable pesticides was studied to contribute in solving the problem of liquid injection of flowable pesticides. Hart and Gaultney (1989) developed and tested a prototype of laboratory direct injection system for dry flowable agricultural pesticides. They designed a variable volume metering/crushing (VVMC) screw to reduce packaged formulation particle sizes, meter formulations, and introducing it into a hydraulic conduit. The unit reliably metered and successfully mixed pesticides into a liquid conduit. However, the tested DIS was not compatible with all dry flowable pesticide formulations. As a next step, Hart and Gaultney (1991) tested an improved design based on a near-constant volume screw to broad the range of commercially available dry flowable pesticide formulations in the previously developed direct injection system in order to reduce screw operating temperatures, improve the output characteristics and particle size distribution over a broader range of dry flowable pesticides. They tested this screw apparatus with a laboratory scale agricultural sprayer equipped with 8004 flat fan nozzles and 50 mesh screens. Four dry chemicals (Lorex at 0.98 kg/ha, Gemini at 0.98 kg, Lexone at 0.56 kg and Preview at

0.56 kg) were injected into the liquid carrier for evaluating liquid dispersion, including dispersion times and formulation metering. Results indicated that dispersal times for packaged formulations were lengthy but reduced with increasing agitation. Reduction of the formulation particle size was also found to decrease dispersal time. Tests indicated that metering and crushing were consistent, repeatable and successfully reduced the formulation to a quickly dispersible particle size.

Falini and Gaultney (1995) patented an apparatus for direct in-line injection of particulate compositions in spraying systems. The invention was an improvement of the precedent screw design developed by Hart and Gaultney for providing a simple and practical method for direct injection of particulate compositions. According to the inventors, it would be advantageous to directly inject solid and particulate compositions because they have many desirable characteristics relative to liquids, including easier handling, storage, package disposal and less potential for worker exposure.

Impact of DIS to limit exposure to pesticide

Handling of agricultural chemicals potentially poses health risks to farmers and custom applicators. Transporting, pouring, and mixing liquid chemicals are especially risky due to splashing, dripping, and spillage onto skin or clothes. Leftover chemicals in sprayer bulk tanks must be disposed of, resulting in the introduction of excess chemicals into the environment (Tompkins et al., 1990). Awareness of the operators' exposure to pesticides during measuring, pouring and mixing, concentrated formulations, leaded to evaluation of risk and development of different engineering solutions for sprayers. Recently, a great concern arises to overcome problems of operator's contamination and environmental pollution due to pesticide handling during spraying operations. The protection of worker from pesticide effect had led to development of sprayers equipped with technical package to limit or eliminate exposure to hazardous substances.

The project EOS (Environmentally Optimised Sprayer) evaluated how spray equipment can contribute to the mitigation of chemical losses to water through the two main entry routes of point and diffuse sources. The point sources concern the handling of chemical on farm during cleaning, filling, remnant management, transport and storage. However, diffuse sources are due to run-off from fields after application and to off target deposition of drifted spray.

The biggest risks for point sources pollution are cleaning and filling sprayers and management of diluted remnant liquids resulting from sprayer filling, cleaning or maintenance work (Roettele et al., 2012). The amendment of the machinery directive (EC/127, 2009) came in force in 2011 to mention the aspect of environmental protection related to sprayers' design and performance.

According to Matthews (2007), closed transfer system and direct injection techniques are of importance to be integrated in sprayers' designs for reducing environmental pollution with elimination of tank mixing and washing of pipeline prior to injection point. Craig et al. (1993) developed a closed transfer system (CTS) based on a venturi injector for hand operated sprayer. The design limits the contact of operator

with pesticide concentrate contained in a bag inside a leak proof bottle screwing into the lance of the sprayer. The concentrate is injected into the lance where it is mixed with water pumped from the tank. The test of the CTS for different formulation viscosities showed a consistent dilution rates between 0.5 and 10% for an overall flow rates between 0.5 and 2 L/min.

Awadhwal et al (1993) designed and tested CTS suitable for use with knapsack sprayers. They found that use of the CTS resulted in low operator exposure compared with the exposure resulting from the mixing and pouring method. They also noted that integration of CTS to knapsack sprayer reduces the frequency of handling concentrated chemicals from the usual 8 to 12 times per day to only once or twice a day, which considerably reduced operator contamination.

Context of VRT technologies development

Development stages of VRT technologies

According to Stone et al. (2008), the potential of applying microprocessor-based technology in agricultural equipment was greatly increased with the first introduction of microcontroller in 1976. The first sprayer control system in USA was commercialized by Raven Industries Company in 1978. Midwest-technologies Company presented its first model of chemical injection sprayer control in 1980. Giles et al. (2008) stated that early introduction of electronics into spray application technology began in the 1980s with simple rate controllers. These devices monitored the ground speed initially by tachometer-type sensors and later by radar sensors to adjust the liquid pressure and maintain the desired application rate.

Since the 1980s, development of control solutions for precise chemical application became of importance to satisfy requirements of emerging modern agriculture. There was a clear effect of technologies progress in automation and process control to induce and promote research and development of precise farming technologies. According to Bode and Bretthauer (2008), the progress of variable rate application technology has been perceived through two development stages put into global context of precision agriculture.

The first stage was noted by the appearance of microprocessors for use in the field of agriculture and development of application rate controllers for adaptation to conventional sprayers. However, extension of such equipment was dependent on development of most reliable and affordable control systems. Although, the trend in developing spraying equipments was towards integration of greater degree of automation; possibilities of designing more efficient control system were not yet used up (Hughes and Frost, 1985).

The second stage starts from 1990s when a remarkable development of electronics, computer sciences and process control technologies had been made. This progress in those technologies has a great impact on the emergence of farming precision technologies. The promotion of variable rate application was technically assisted by development of process control systems and tendency of designing cost effective technologies. Otherwise, recommendation for keeping chemical application error

within 5% (USDA, 1989) speeded up development of electronic control systems for reliable and efficient sprayers having the ability to reduce errors and undesired variation in chemical application rate (Steward et al, 2000).

Bode and Bretthauer (2008) stated the importance of development of electronic and process control technologies in improving performance of spraying technologies by reducing chemical application errors and avoiding human exposure and environment contamination. In this context, the development of new chemical application technologies such as direct injection, on-board application systems and control systems contributed for improving application efficiency and protecting the environment (Bode and Bretthauer, 2008).

Research progress of DIS technologies

From 1970s to 1990s, R&D process was interested only on testing and evaluation of VRT and DIS options. Developers implemented different hydrostatic and pneumatic solutions coupled to simple process control methods. There was an extensive technological progression softly influenced by the shifting from classic mechanic to mechatronic with use of digital solutions and computer science. After that, researcher interested to improve dynamic performance of DIS with accordance to development shown in digital electronic for developing new VRT prototypes.

The first attempt of designing a DIS system has been done in early in 1970s (Amsden, 1970; Gohlich; 1970; Vidrine et al., 1975). Vidrine et al. (1975) developed a DIS prototype using a positive displacement metering pump to inject chemical into the spraying boom. The carrier flow rate was constantly maintained by a hydro-pneumatic pressure of a compressed tank. The metering pump speed was actuated proportionally to ground speed for centrally injecting chemical at the boom level. Schmidt et al. (1983) developed a direct injection system using a venturi nozzle for chemical metering. The prototype was designed to split the carrier flow into two lines for acting the venturi through the injection line of the chemical flow reconnected to the carrier flow line before mixture application at the boom level. Gebhardt et al. (1984) evaluated two injection metering strategies by actuating a positive-driven pump via an open-loop control system and by monitoring a pump with a flow meter serving as consign for a close-loop control system. The concentrated chemical was pumped from the container through a control valve regulated by a controller.

Chi et al. (1988) designed and tested a flow control system using electro mechanical feedback for a positive displacement pump as a metering pump system. The feedback system kept the pressure drop across the metering pump at zero and controlled the metering pump speed according to the desired flow rate. The test results showed that the system worked well for fluids with varying viscosities from 90 to 300 mPa.s and flow rates from 3 to 20 mL/s. A linear relationship was drawn between the flow rate and pump speed. The response time performance test showed that the system reached the steady state with a maximum of 5 s after start or during the travel speed change. Frost (1990) proposed a hydrostatic metering system in which the carrier is pumped to the nozzles with a constant pressure. Some water is extracted from the lines feeding nozzles and sent by the metering pump into the cylinder containing the chemical. Water and chemical are separated in the cylinder by

a free piston or a flexible membrane. A metered flow of a carrier displaces the chemical, which is injected into a mixing chamber where it is mixed with the carrier and delivered to nozzles.

Since 1990s, scientists investigated NDIS for improving reaction time of spraying systems to satisfy requirements of site specific spraying as a main option of variable rate application and map-based precision farming. As shown before, NDIS presents advantages to improve reactivity of direct injection system but cannot be done without affecting online mixing process of chemical. Several authors (Tompkins et al., 1990; Miller and Smith, 1992; Rockwell and Ayers, 1996; Bennet and Brown, 1997; Walker and Bansal 1999) investigated different configuration of DNI with use of metering systems for precise chemical flow control. Compared to DIS configurations using central or boom injection points, NDIS has the advantage of significantly reducing lag transport for use in map-based precision farming.

Commerce state of DIS technologies

According to Koo and Sumner (1998), many direct injection systems have been tested and evaluated but the control systems trademarks are mainly commercialised by the Midwest-Technologies, Inc., Raven Industries, Micro-Track Systems, Inc., and BEE Ag-Electronic.

The main trademarks of direct injection spraying technologies have been marketed for the first time in North America according to the favorable context of big scale farming. The North American market is dominated mainly by the trademarks of Mid-technologies and Raven industries:

The Midwest-technologies has proposed two direct injection control systems, the TASC 6600® and the Legacy 6000® that can be equipped with a MT500 peristaltic injection pump or a MT600 piston injection pump. Both systems can be set to monitor different chemical specialties in a parallel scheme of one to three tanks. The system designated for injecting chemical in downstream point to the carrier pump, is equipped with a positive displacement piston pump unit giving a common flow rate ranging from 0.015 to 7 L/min. The pumps are driven by 12 V variable-speed electric motors through the electronic controller.

The Raven® Industries is commercializing a Sidekick Pro™ and Sidekick™ direct injection systems that can be monitored by the SCS or DCS control consoles. The Raven designs are adaptable to existing conventional sprayers. Both systems are based on a variable-stroke piston pump which meters chemical into the pressured side of the carrier flow line. The maximum operating pressure can reach 10 bars by controlling pump speed for increasing chemical flow rate. The control is done with respect to feedback of flow meter integrated into the pump body. The Sidekick Pro™ direct injection system is designed to deliver a maximal capacity of carrying four chemicals in parallel scheme at once.

John Deere Company developed a “Direct Injection Ready” system mounted in self-propelled sprayer JD 4990. The system is designed to inject in centrally point up to four high volumes and one low volume of different formulations. The metering system

is based on two piston pumps adapted for high and low flow rate ranges to inject in online mixer situated in pressure side between the main pump and distributor serving the boom sections.

Berthoud Company (2012) developed a DIS based on metering pumps and hydro cyclone to inject simultaneously up to three products upstream to a sprayer main pump. The injection system is adaptable for sprayers equipped with electronic system used to control flow rate proportionally to forward speed (DPAE). This DIS improves online mixing quality with its hydro cyclone concept but reactivity of the system and application uniformity in the traveling direction is affected by consistence of lag transport due the hydro cyclone dead volume and the upstream position of injection point.

Spray Concept Company developed the direct injection SP-ID that can dose separately up to four formulations in upstream side of a sprayer main pump. ARVALIS-Institute (2012) tested performance of SP-ID and SIDEKICK PRO systems mounted on conventional sprayers for applying modulated dose rate on the field. The test results showed that response time of both systems varied between 60 and 80 s depending on dead volume of the sprayer hydraulic circuits. This delay time potentially caused spraying misapplication up to 220 m for typical working speed of 10 km/h but it can be taken into account for application based on the prescription map.

Hardi Company (1997) developed a direct injection spraying system for “need dosage” based on CDIS with downstream injection point for applying chemical at a maximal permissible concentration related to a maximal operating speed in the field. However, this method needs pre-dilution of concentrated formulation which potentially presents risk of contamination during handling of chemical. This later cannot be recuperated for further use after the pre-dilution. The need dosage method is proposed to limit effect of potential concentration application error arising from slightly incorrect dosage of highly concentrated formulations need to be mixed with water. The design is presented as a solution to avoid risk of amplifying metering error of using concentrated chemical from one tank.

Amazone Company developed also a direct injection system based on premixing the pesticides with water in a proportion of 10% volume of the dilution tank. The premixing solution limits the dimension of the injection device to operate with a constant pesticide volume independently of the initial volume of active ingredient. The chemical premixed solution is injected into the carrier downstream of the carrier pump in front of the boom section valves (Hloben, 2007).

The hydraulic injection system Agroinject is a trade mark developed by MSR-Ciba-Geigy Company. Its principle consists on actuating the metering pump by the carrier water flow to proportionally inject chemical through spray booms. The dosing pump can suck chemical from their original containers in a closed transfer way of chemical to avoid the contact and potential contamination of the operator. The powdery formulations must be pre-diluted in water before a direct injection application. The company Tecnoma implemented their conventional sprayers with Dosatron DIS. This system is based on the same principle of Agroinject using main pressure energy of carrier flow for actuating the metering pump (Hloben, 2007).

The Micron Sprayers Company (U.K) developed an injection system based on a syringe cylinder container which can be used for extracting and metering chemicals into the carrier. The evaluation of this metering device showed a limited performance with viscous pesticides due to a lack of linearity in pressurizing the plunger in the cylinder container (Frost, 1990).

LECHLER Company developed a direct injection system based on a hydraulically driven piston pump to deliver pesticides from two different containers in a range of 0.2 to 5 L/ha. This system is equipped to return unused chemicals to their containers and to rinse the hydraulic circuit (Hloben, 2007).

The Dos-Intro DIS trade mark uses a needle valve for metering the pesticide into the carrier flow in front of the boom section valves. The needle valve is actuated by electric motor on the basis of the wheel flow meter feedback for adjusting the pesticide flow rate into the mixing chamber. The pesticide is delivered from air pressured tank supplied by pneumatic compressor (Lammers et al., 2010.

Perspectives of developing low cost DIS technologies for developing countries

Commercialization of DIS trademarks is mainly promoted in developed countries. Progress of precision farming in the context of big scale farming boosted use of DIS to solve problem of mixing high quantities of herbicide applied in no-till agricultural system. Until now, use of DIS technology kept concentrated in big scale farming of developed countries of North America and Europe. Adoption of DIS technologies in developing countries is constrained by high initial cost and maintenance requirements. Furthermore, existing DIS technologies are not adapted for use in the context of medium and small scale farming.

Development of low cost DIS technologies can be promoted trough development of low cost spraying control systems. Practically, design of affordable control systems is now possible according to considerable development of process control and sensors technologies.
As low cost solution, the injection of chemical at low pressure in suction side requires usage of simple and affordable peristaltic metering pump (two to five times lower price) with low energy requirement (five to ten times lower consumption) comparatively to exigency of injection in pressurized side.

The technique of injecting in upstream injection point is an interesting option of online mixing of chemical through the main pump without use of online mixer that can economically reduce energy use due to friction loss and cost of the mixer device. This choice can improve cost and energy efficiency of the pretended DIS design. However, the dynamic performance of upstream injection can be maintained as there is a flexibility of placing electrical pumps closes to boom line in order to reduce distance and dead volume between injection and tip nozzles points. Hydraulic boom design can be optimized to reduce lag transport and improve reactivity of DIS.

El Aissaoui et al. (2011) developed a small electrical DIS based on rechargeable batteries. Use of technical options of injection in low pressure side and usage of hydrodynamic mode control are showed an efficient energy use for higher autonomy.

By choosing electrical motors for pumps, it was possible to install pumps closely to the spraying boom and overcoming problem of lag transport. This choice improves the dynamic performance of DIS and has a fast reaction time for optimal processing of concentration change (El Aissaoui et al., 2011).

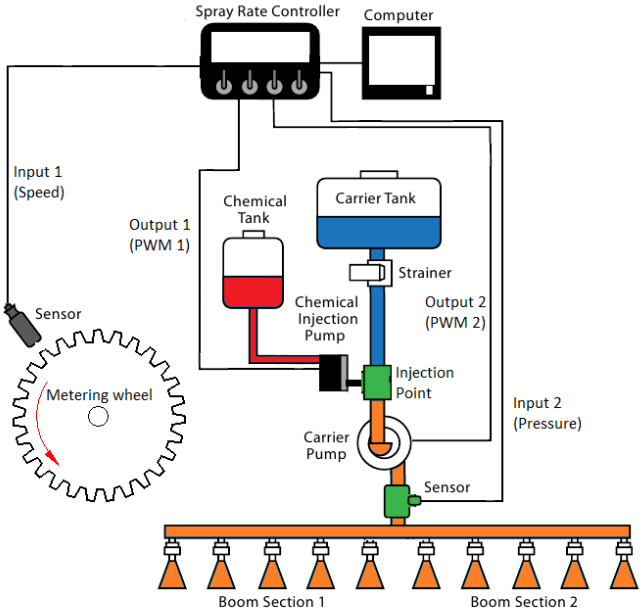

Figure 5: Layout of a low cost electrical DIS prototype based on speed control feedback (El Aissaoui, 2016)

Conclusions

According to the usage context of DIS, the technology progress keeps focused on searching solutions for precise and easy chemical application in big scale farming of developed countries. There isn't yet any interesting offer for small scale farming despite of different attempts to adopt technology in some developing countries (case of India). The technology adoption is economically constrained by its high cost and lack of DIS offers adapted for the context of small scale farming.

Remarkable research progress has been done to improve design of existing DIS and variable rate controller's performances in term of lag transport and system dynamic reactivity but the complexity of DIS keeps in solving the controversy between the parameter's performances. In fact, uniform mixing of chemicals into the carrier and easy cleaning of contaminated parts with concentrated pesticides cannot be perfectly done while looking for better dynamic performance in adopting local points injection and shortcut mixture transport (case of BDIS and NDIS). Otherwise, the complexity also keeps in designing cost effective and energy efficient DIS.

Use of DIS technology is only available for big scale farming in developed countries. Adoption of this technology in developing countries cannot be easily done because of the high cost of existing technological offers. It is possible to promote local development of low cost VRT and DIS technologies. This process of development can be considerably boosted with remarkable development of process control and sensors technologies.

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List of Abbreviation

AI	Air induction
ASABE	American Society of Agricultural and Bio resource Engineering
BDIS	Boom direct injection system
CDIS	Central direct injection system
CCFC	Constant carrier flow control
TFC	Total flow control
DPAE	Electronic spray control of proportional flow rate to forward speed
DIS	Direct injection system
PWM	Pulse Width Modulation
VRT	Variable rate Technology
TAR	Technical application rate of chemical formulation
USDA	United States Department of Agriculture
VVMC	Variable volume metering/crushing

References

Alamouti Y. M. and M. Sedaghat H. (2014). Response time of a direct injection type variable-rate sprayer. Agric Eng Int: CIGR Journal, 16(3). p. 70－76.

Amsden R.C. (1970). The metering and dispersing of granules and liquid concentrates. British Crop Protection Council, Monograph 2. p. 124–129.

Anglund E. A., and Ayers P. D. (2003). Field evaluation of response times for a variable rate (pressure-based and injection) liquid chemical applicator. Applied Engineering in Agriculture 19(3). p. 273-282.

Arvalis (2012). Measurement of reactivity of two direct injection systems. Technical report 2012.

Awadhwal N. K., Quick G. R., and Cabrido E. F. (1993). Closed chemical transfer for knapsack sprayers. Applied Engineering in Agriculture, Vol. 9(1). p. 7-9.

Bennet, K. A. and Brown R. B. (1997). Direct nozzle injection and precise metering for variable rate herbicide application. ASAE Paper N° 97-1046. St. Joseph, MI: ASABE.

Berthoud (2012). Direct injection clean sprayer. Technical report.

Baio F. H. R. and Balastreire L. A. (2002). Development of method to determine the time of response of an injection metering system. World Congress of Computer in Agriculture, ASABE Pub 701P0301, 13 March 2002.

Bode, L., Bretthauer, S. M. (2008). Agricultural chemical application technology: a remarkable past and an amazing future. Trans. ASABE 51(2). p. 391-395.

BBA (2005). List of Plant Protection Products, Part VI: Approved crop protection equipment, 52th edition.

Budwig, R. S., McDonald J. M., and Karsky T. J. (1988). Evaluation of chemical injection systems for mobile agricultural spray equipment. ASABE Paper No. 88-1592. St. Joseph, MI: ASABE.

Bui, Q.D. (2005). Varitarget-A new nozzle with variable flow rate and droplet optimization. Paper number 051125, 2005 ASAE Annual Meeting .

Cai X., Walgenbach M., Doerpmond M., Lammers P. S. and Sun Y. (2016). Closed-loop control of chemical injection rate for a Direct Nozzle Injection System. Sensors 2016, 16(1). p. 127.

Chi, L., Kushwaha, R. L. and Bigsby, F. W. (1988). Chemical flow rate control in injection-type sprayers. Can. Agric. Eng. 30. p. 19-26.

Craig I. P., Matthews G. A.,and Thornhill E. W. (1993). Fluid injection metering system for closed pesticide delivery in manually operated sprayers. Crop Protection, 12(7). p. 549-553.

DörpmundM.(2012). Pesticide reclamation and cleaning of direct nozzle injection systems. Doctoral thesis, University of Bonn, 128p.

Daggupati N.P. (2007). Assessment of the varitargetnozzle for variable rate application of liquid crop protection products, Master thesis, Kansas State University.

El Aissaoui A., F. Lebeau, L. Lbahir, M-F Destain, K. Houmy. (2011). Development of a process control system for potential use of direct injection spraying technology. Journal of Progress in Agricultural Engineering, 7(3), AkadémiaiKiadó, Hungary.

El Aissaoui A., 2016. A Feasibility Study of Direct Injection Spraying Technology for Small Scale Farms: Modeling and Design of A Process Control System. Doctoral thesis, University of Liege, 175p.

El Aissaoui A., Khnizrou L., Houmy K., Bouzrari B. (2018) Development of Direct Injector for Management of Residual Chemical Due to Use of Stationary Spraying System in Greenhouse Crop Production. AgEng 2018 conference, Jully 8-12th, Wageningen, Netherlands.

Falini J. P., and Gaultney L.D. (1995). Direct in-line injection of particulate compositions in spraying systems. United States Patent N° US005383611A.

Felizardo K. R., H. V. Mercaldi, P. E. Cruvinel, V. A. Oliveira, B. L. Steward (2016). Modeling and Model Validation of a Chemical Injection Sprayer System. Applied Engineering in Agriculture. 32(3). p. 285-297.

Frost A.R. (1990). A pesticide injection metering system for use on agricultural spraying machines. Journal of Agricultural Engineering Research. 46(2). p. 55–70.

Gebhardt M.R., Klietheres A.R., Goering C.E. (1984). Metering concentrated pesticides. Transactions of ASAE 27(1). p. 18-23.

Giles D.K., Akesson N.B, and Yates W.E. (2008). Pesticide application technology: Research and development and the growth of the industry. Transactions of the ASABE. Vol. 51(2). p. 397–403.

Gohlich, H. (1970): Development tasks in Plant Protection. LandtechnischeForschung 18. p. 95-99.

Hardi (1997).A spray system for need dosage. Patent WO1997016964 A1.

Hart W. E. and Gaultney L.D. (1989). A direct injection system for dry flowable agricultural pesticides. ASAE Paper No. 89-1610. St. Joseph, MI: ASAE.

Hart W. E. and Gaultney L. D. (1991). A constant volume feed device for metering and crushing dry pesticides. Transactions of the ASABE, Vol. 34(1). p. 27-32.

Hloben P., (2007). Study on the response time of direct injection systems for variable rate application of herbicides. Doctoral thesis, 184p, University of Bonn, Germany.

Hoogterp A. (2009). Map-based spraying with a direct injection, Master thesis, Wageningen University.

Hughes K.L and Frost A.R. (1985). A review of agricultural spray metering. Journal of Agricultural Engineering Research 32(3). p. 197-207.

Koo Q.M., Young S.C., Kuhlman D.K. (1987). Flow characteristics of injected concentrates in spray booms. ASABE Paper N° 87-1602. ASAE, St. Joseph.

Koo Q.M. and Kuhlman D.K. (1993). A variable flow nozzle with consistent spray performance. Transaction of the ASABE 36(3). p. 685-690.

Koo Q.M., and Sumner H.R. (1998). Total flow control for direct injection sprayer. Applied Engineering in Agriculture 14(4). p. 363–367.

Landers A. J. (1992).Direct injection systems on crop sprayers. The Agricultural Engineer 47(1). p. 9 - 12.

Lammers P. S. and Vondrika J. (2010). Direct injection sprayer. Chapiter 18, Pricision crop protection- the chalange and use of heterogeneity, Springer edts, ISBN: 978-90-481-9276-2.

Luck J. D., Shearer S. A., Sama M. P. (2019). Development and Preliminary Evaluation of an Integrated Individual Nozzle Direct Injection and Carrier Flow Rate Control System for Pesticide Applications. Transactions of the ASABE 62(2). p. 505-514.

Luck J. D., Shearer S. A., Luck B. D., and Payne F. A. (2012). Evaluation of Rhodamine-WT dye/Glycerin mixture as a tracer for testing direct injection systems for agricultural sprayers. Applied Engineering in Agriculture 28(5). p. 343–346.

Matthews G. A., (2007). Developments in application technology. Environmentalist Vol 28. p. 19-24.

Miller, M. S. and Smith. B. (1992): A direct nozzle injection controlled rate spray boom. Transactions of ASAE 35(3). p. 781-785.

Miller, P.C.H.,Paice, M.E.R. and Ganderton A.D (1997). Methods of controlling sprayer output for spatially variable herbicide application. Proceedings Brighton Crop Protection Conference on Precision Agriculture – Weeds, 1997. p. 641-644.

PAMI (1988). Summers Model 9FS3421 skid mounted field sprayer. Evaluation report 577. Humbold, Saskatchewan, Canada: Praire Agricultural Machinery Institute.
Paice, M. E. R., Miller, P.C.H. and Day W. (2001): Control requirements for spatially selective herbicide sprayers. Computer and Electronics in Agriculture 14. p. 163-177.

Pierce R. A. and Ayers P. D. (2001).Evaluation of Deposition and Application Accuracy of a Pulse Width Modulation Variable Rate Field Sprayer. Paper number 011077, ASAE Annual Meeting, 2001.

Qiu, W., Watkins G.A., Sobolik C.J. and Shearer S.A. (1998). A feasibility study of direct injection for variable-rate herbicide application. Transactions of the ASAE 41(2). p. 291-299.

Rockwell A.D. and Ayers P.D. (1996). A variable rate, direct nozzle injection field sprayer. Applied Engineering in Agriculture 12(5). p. 531–538.

Roettele M., Balasari P., Doruchowski G., and Wehmann H. J. (2012). Environmentally Optimised Sprayer (EOS): Evaluation of spray equipment to mitigate point and diffuse source losses of plant protection products to water. International Advances in Pesticide Application, Hof Wageningen, Wageningen, Netherlands, 10-12 January 2012. Aspects of Applied Biology, No.114. p. 143-150,

Ruixiu S., Thomson J. A., and Wiellers J. L., Lee F. P., Wang P. (2003). Variable rate spray dynamic evaluation, paper N° 031128, ASABE annual meeting 2003.

Stafford, J. and Miller, P.C.H (1993): Spatially selective application of herbicide to cereal crops. Computers and Electronics in Agriculture 9(3). p. 217-229.

Steward, B. L., Humburg, D. S. (2000). Modeling the raven SCS-700 chemical injection system with carrier control with sprayer simulation. Transactions of the ASAE 43(2). p. 231-245.

Stone M., (2000). Design of agricultural chemical applicator, Course 3213, Agricultural Engineering department, Oklahoma State University, http:www.oksu.us, accessed in mars 2013.

Sudduth K.A., Borgelt S.C. and Hou J. (1995). Performance of a chemical injection sprayer system. Applied Engineering in Agriculture 11(3). p. 343–348.

Tompkins, F. D., Howard, K.D., Mote C.R. and Freeland R.S. (1990). Boom flow characteristics with direct chemical injection. Transactions of the ASAE 33(3). p. 737-743.

USDA and EPA (1989). Applying pesticides correctly, a guide for private and commercial applicators, 72. U.S. Department of Agriculture and the Environmental Protection Agency.

Vidrine, C.G., Goering, C.E., Day, C.L., Gebhardt, M.R. and Smith, D.B. (1975): A constant pesticide application rate sprayer model. Transaction of the ASAE 18(2). p. 439-443.

Vondricka, J., and Lammers P. S. (2009). Evaluation of carrier control valve for direct nozzle injection system. Biosystem Engineering 103. p. 43–48.

Walker J.T., and Bansal R.K. (1999). Development and characterization of variable orifice nozzles for spraying agro-chemicals. ASABE Paper No 99-1008. ASAE, St. Joseph.

Zhang Z., Zhu H., Guler H. and Shen Y. (2019) Improved premixing in-line injection system for variable-rate orchard sprayers with Arduino platform. Computers and Electronics in Agriculture 162. p. 389–396.

Zhu H., Ozkan H.E., Fox R.D., Brazee R.D. and Derksen R.C. (1998). Mixture uniformity in supply lines and spray patterns of a laboratory injection sprayer. Transactions of ASAE Vol.14(3). p. 223–230.