Computers and Electronics in Agriculture 162 (2019) 389–396

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Improved premixing in-line injection system for variable-rate orchard sprayers with Arduino platform

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ARTICLE INFO

Keywords:
Pesticide
Air-blast sprayers
Metering pump
Mixture uniformity
Precision agriculture
Automation

ABSTRACT

To reduce the tank mixture leftover problem associated with variable-rate orchard sprayers, an experimental automatic premixing in-line injection system was developed with Arduino platform. This system primarily consisted of a precision fluid metering pump, a water pump, a static mixer, a premixing tank and a buffer tank. The required amounts of water and chemical concentrates were accurately pumped into the premixing tank through a static mixer. The mixture was then transferred into a buffer tank for additional mixing process and for the spray pump to discharge to variable flow-rate nozzles. When the buffer tank neared empty, this process was repeated automatically to maintain the same chemical ratio for all nozzles regardless of their spray output differences and variations. Accuracy of the metering pump was verified with simulated pesticide concentrates (tap water, turpentine oil, prime oil, and four different viscous sucrose solutions) at viscosities between 0.9 and 32.0 mPa·s. With addition of a fluorescent tracer, the sucrose solutions were also used to evaluate the uniformity of spray mixtures discharged from the premixing in-line injection system. Test results demonstrated that the fluid metering pump could accurately dispense desired volume (10–300 mL) of simulated pesticides at different pump rotational speeds with relative errors between measured and desired volumes below 5%. The uniformity of spray mixtures at different chemical-to-water ratios (0.1%–2.0%) was consistent, and the highest relative error and coefficient of variation were 7.6% and 4.5%, respectively. The experimental premixing in-line injection system was proven to have stable and accurate performance, and thus would have great potentials to improve spray application efficiency with minimized tank mixture leftovers for future variable-rate sprayers.

1. Introduction

Pesticides have been progressively used to protect crops in the world agriculture to obtain high productivity and quality supply of food (Carvalho, 2006; Popp et al., 2013). Unfortunately, despite these achievements, the widespread use of pesticides has caused severe potential environmental contaminations (WHO, 2010; Rathore and Nollet, 2012; Edwards, 2013) and health hazards to human beings (Bryden et al., 2005; McCauley et al., 2006; Baltazar et al., 2014). One of the problems is the exposure of applicators to hazardous concentrated pesticide during loading and mixing (Zhu et al., 1998; Grover et al., 2003; Singh et al., 2011). Applicators mix chemical concentrates with carriers in large tanks before they go to farm fields to spray plants. It is reported that sprayer operators usually work under time-pressured operating conditions, and they have to finish the application tasks within a short window without much time to take all the necessary precautions to prepare tank mixtures (Austin et al., 2001).

Another problem associated with sprayers is the disposal of excess tank mixture and washed water. Sprayer operators must dispose whatever the amount of spray mixture is left in the tank and the washed water used to clean the tanks after applications, which wastes time and materials. Furthermore, both the operator and the environment are exposed to the toxic agrochemicals (Reichard and Ladd, 1983). This problem also exists for variable-rate spraying systems because the required volume of tank mixture to be applied varies with plant size, shape, foliage density and growth stage. It is difficult for applicators to prepare the exact amount of tank mixtures needed before they go to the field to spray crops. As a result, excessive tank mixture leftover can be inevitably encountered. Therefore, real-time in-line injection systems are needed for variable-rate spraying systems to solve the problems such as pesticide exposure, tank mixture leftover and washed water disposal associated with conventional spray technology (Shen and Zhu,

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https://doi.org/10.1016/j.compag.2019.04.023
Received 26 October 2018; Received in revised form 12 April 2019; Accepted 18 April 2019
Available online 28 May 2019

2015).

To eliminate the tank mixture leftover problem for conventional constant-rate sprayers, in-line injection systems to discharge concentrated pesticide formulations directly into the carrier stream or nozzles have been investigated and improved over past several decades (Amsden, 1970; Reichard and Ladd, 1983; Marchant and Frost, 1989; Way et al., 1990; Ghate and Perry, 1994; Sudduth et al., 1995; Womac et al., 2002; Gillis et al., 2002; Downey et al., 2006; Vondricka and Lammers, 2009, Lammers and Vondricka, 2010; Felizardo et al., 2016; Pohl et al., 2017). However, as explained by Shen and Zhu (2015), these conventional direct in-line inject systems cannot be used for variable-rate sprayers because of their unsolved problems associated with the long lag time, inconsistent mixture uniformity and inaccurate dispense of very low chemical flow rates. Also, spray outputs from variable-rate sprayers can be suddenly changed from zero to full capacity due to instant changes in plant canopy structures and plant presence or absence status. To maintain a constant chemical ratio in the spray mixture to be discharged from every nozzle in the variable-rate mode, it would require chemical pumps to dispense chemicals into carrier lines with widely variable ranges instantaneously to respond the sudden changes of the spray outputs. However, there are no such available metering pumps or valves capable of responding such sudden changes precisely.

In this research, an improved experimental premixing in-line injection system was developed based on the previous prototype developed by Shen and Zhu (2015). Compared to the previous prototype, the novelties of this research could be summarized as the following aspects: the new prototype used Arduino circuit board as a development platform, gaining more accessibility, stability and cost versus functionality for the project tasks; accuracy of dispensing fluids was evaluated at a wider range, ensuring greater capability of the system; maximal ratio of chemicals in spray mixtures was increased from 1% to 2%, allowing more flexibility to choose pesticides for applications.

To fulfill these improvements, the objectives of this research were to: (1) design, build and test an automatic premixing in-line injection system prototype developed with the Arduino platform; (2) determine the system accuracy of dispensing simulated pesticides of different viscosities; (3) evaluate the mixing uniformity of spray mixtures discharged from the system.

2. Materials and methods

2.1. Premixing in-line injection system functions

The layout of the key components for the premixing in-line injection system is shown in Fig. 1. This system mainly consisted of a water tank, a premixing tank, a buffer tank, a chemical tank, a fluid metering pump, a water pump, a static mixer, liquid detection sensors, a microprocessor control unit, and an embedded computer with touch screen. It was a semi closed feed-back system.

The spray process with the system was performed as following steps: first, desired amounts of water and chemical concentrates were separately dispensed into the static mixer (Model 1/2-40C-4-12-2, Koflo Corporation, Cary, Illinois, USA) in a liquid line and discharged into the premixing tank, and then the water-chemical mixture was transferred into a buffer tank for the spray pump to discharge to variable-rate nozzles. This process assured that the spray mixture ratio remained the same for all nozzles regardless of variations in their spray outputs. Water level sensors produced digital signals to notify the microcontroller board whether premixing tank or buffer tank neared empty. Accordingly, the microcontroller released commands to the pump driver and the metering pump controller simultaneously for the water pump and the metering pump to deliver desired amounts of water and chemical concentrates into the premixing tank. Digital signals were generated from the two water level sensors in the buffer tank for the controller to open and close the electric motor valve for refilling the buffer tank.

The microprocessor control unit mainly consisted of an Arduino circuit board (Model Arduino Mega 2560 Rev3, SparkFun Electronics, Niwot, Colorado, USA). As shown in the flowchart (Fig. 2), the circuit board acquired the desired ratio of chemicals inputted through touch screen on the embedded computer (Model AFL-07A, Series N270, IEI Technology, Pomona, California, USA). Based on the ratio input, the optimum metering pump speed was assigned by Arduino board automatically. The required volume of concentrated chemicals was then determined. The specific injection time needed by the metering pump to discharge the required volume of concentrated chemicals was calculated. Afterwards, concentrated chemicals and water were pumped into the premixing tank. When the buffer tank was nearly empty, the electric motor valve was opened and the mixture was transferred to the buffer tank. When the buffer tank was nearly empty, this process was repeated automatically as a new mixing cycle.

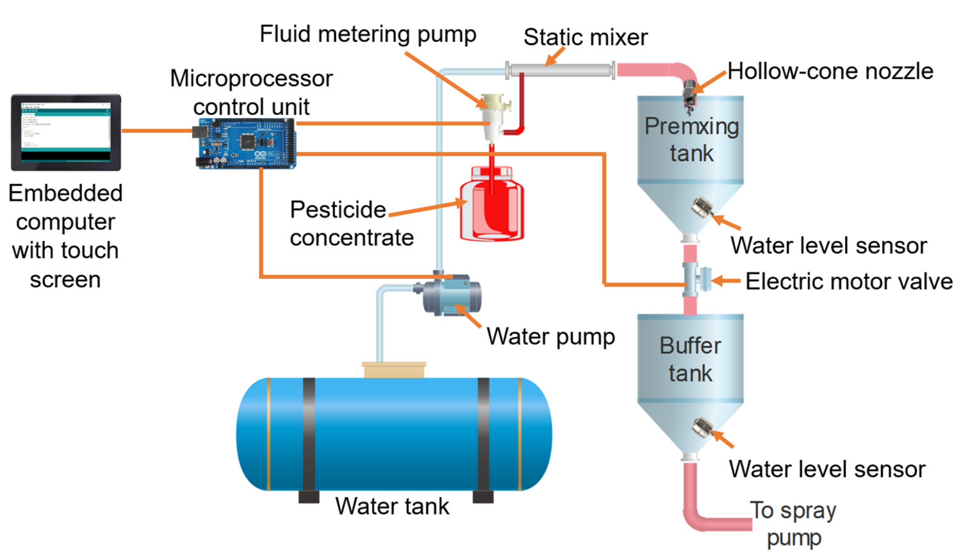

Fig. 1. Layout of the key components used in the premixing in-line injection system.

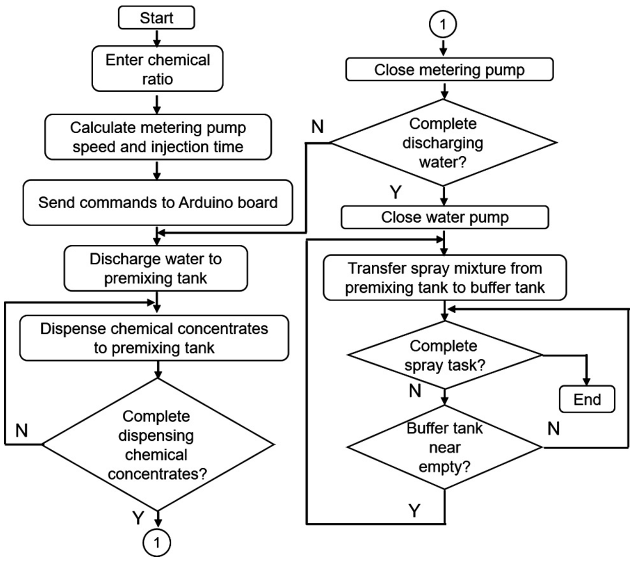

Fig. 2. Flowchart of the computer program for managing the premixing in-line injection system operation.

2.2. Key components

The metering pump was one of the key components in the system because it ensured accuracy of metering pesticides to reach desired mixture ratios based on the dosage rate specified on the chemical label. In this research, a ceramic piston pump with stainless-steel body driven by a step motor was used as the metering pump (Model STQ 2, Fluid Metering, Inc., Syosset, New York, USA) to dispense the desired amount of chemical concentrates (Fig. 3). The amount of chemical concentrates was controlled by synchronizing the piston rotation speed and number of pulses triggering the step motor rotation (Shen and Zhu, 2015). The synchronization function was manipulated with a microprocessor controlled circuit board (Model SCST-01, Fluid Metering, Inc., Syosset, New York, USA) (Fig. 3).

The microprocessor controlled circuit board recognized and responded to an external 0–5 VDC control signal input to adjust the step motor speed and then the metering pump rotational speed. The step motor speed varied linearly with the VDC voltage. Depending on the application, the maximum speed using a 0–5 VDC input signal control was limited to 1200 rpm. The volume of fluid discharged from the metering pump was modulated by the operation time duration and the step motor speed. That is, the volume of chemical concentrates dispensed into the mixing line was directly proportional to the metering pump speed and operation time duration. With this design, the chemicals could be precisely controlled within a range of flow rate (5–635 $mL\,min^{-1}$), capable of performing variable-rate tasks with a wide range of chemical ratios.

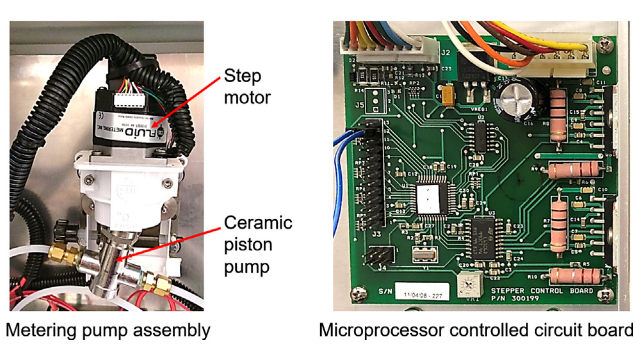

Fig. 3. A ceramic piston metering pump driven by a step motor and manipulated with a microprocessor controlled circuit board to dispense desired amount of chemical concentrates.

The water pump was a diaphragm pump (Model 5500 Series 5538-1E1-94A, REMCO Industries, Alexandria, Minnesota, USA) to discharge water from the water tank to the static mixer (Fig. 1). The volume of discharged water was controlled by time duration through the Arduino controlled unit during each mixing cycle.

To obtain a uniform spray mixture for the variable-rate application, chemical concentrates and water with a desired ratio were first mixed through the static mixer (Fig. 1), and then the mixture flow was further agitated with a turbulent liquid jet discharged to the premixing tank through a large hollow-cone nozzle (Model TF48, BETE Fog Nozzle, Inc., Greenfield, Massachusetts, USA). The nozzle flow capacity was 153 $L\,min^{-1}$ at 50 kPa pressure. A typical flow rate of the static mixer was 2.46–18.93 $L\,min^{-1}$ with pressure loss of 3.45–137.90 kPa. However, this pressure loss would not affect the mixture ratio accuracy because the amounts of water and chemical concentrates discharged to the mixer remained unchanged during all mixing cycles.

The buffer tank must be refilled with the spray mixture from the premixing tank when it neared empty, and the refilling time must be short enough to ensure the spray line was filled with the spray mixture all the time. The refilling process was accomplished by a microprocessor-controlled electric-motor-driven valve (Model 346BEC-25S-C, TeeJet Technologies, Wheaton, Illinois, U.S). The electric motor speed was 25 rpm which enabled the valve to respond quickly within 0.6 s from fully open to close or vice versa. The capacity of the valve was 379 $L\,min^{-1}$ (100 GPM) with a pressure drop of 34-kPa (5 psi). In this system, it took less than 5.2 s to transfer 10 L of spray mixture form premixing tank to buffer tank.

Stainless steel liquid level sensors (Model ZP4510-S, Uxcell, Hong Kong, China) were used to detect the mixture surface in both premixing and buffer tanks. One of the liquid level sensors was located at the bottom of the premixing tank to detect whether the tank was nearly empty. This liquid level sensor was used to trigger both water pump and metering pump to start discharging water and chemical concentrates to refill the premixing tank. Another water level sensor was located at the bottom of the buffer tank to maintain a sufficient amount of spray mixture in the tank.

Arduino Mega was an ATmega processor based prototyping platform, and used C++ language software as the development environment (Fig. 4). It was selected as the automatic controller for the premixing in-line injection system. The platform could be used to manipulate a variety of sensor modules and actuators (Wason and Wen, 2011), and was also a fast tool to assist product development in process control tasks (Juang and Lurrr, 2013) and/or improve intelligent agricultural applications (Polo et al., 2015; Donofre et al., 2018; Ramadan et al., 2018). Moreover, selection of Arduino Mega as the development board for this research was based on their processing speed, available I/O interface and compatibility. (1) Processing speed: the premixing in-line injection system required a real-time response to liquid level signals in premixing and buffer tanks. Thus, the development board must be able to provide a sufficient speed to process tasks including data acquisition, control computation and signal outputs. The Arduino Mega was equipped with the ATmega 2560 processor, featuring a maximum clock rate of 16 MHz. With this rate, a sampling time could be achieved within 0.01 s. (2) Available I/O pins: there were 12 I/O pin-outs from liquid level sensors, water pump and the step motor control kit in the premixing in-line injection system. The Arduino Mega board consisted of 54 general-purpose digitals I/O pins and sixteen 10-bit 0–5 V analog inputs with a quantization limit of 4.9 mV. (3) Compatibility: the Arduino board was complied with useful function libraries and references associated with C++ language.

2.3. Metering pump accuracy verification

To avoid exposure to toxic pesticides in the engineering laboratory, tap water, turpentine oil (Klean-Strip Corp., Memphis, Tennessee, USA),

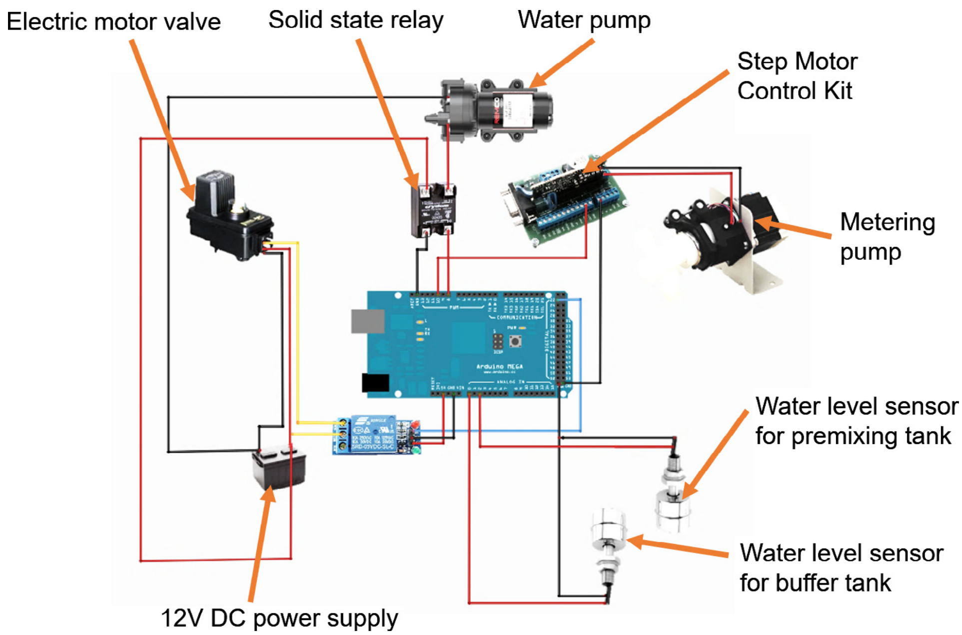

Fig. 4. Schematic connections between Arduino board and primary components used to control the chemical concentrate dispensing process.

prime oil (Riverside/Terra Corp., Sioux City, Iowa, USA) and four different viscous sucrose solutions (Granulated sugar, Our Family Food, Inc., Michigan, USA) were used as simulated pesticides for the tests. Viscosities of water, prime oil and turpentine oil were 0.9, 1.8, and 32.0 mPa·s, respectively, as measured with a portable viscometer (Viscolite 700, Vindum Engineering, Sandpoint, Idaho, USA) at 25 °C. Solutions of sucrose with four concentrations in tap water were prepared for the accuracy evaluation. Viscosities of the four sucrose solutions were 8.0, 16.0, 24.0, and 32.0 mPa·s. The accuracy of the metering pump for dispensing simulated pesticide concentrates with different viscosities were evaluated with four dispensing volumes and three metering pump speeds to verify if its accuracy was unaffected by viscous fluids. The desired dispensing volumes of each simulated pesticide concentrates were 10, 50, 100, 200 and 300 mL. The metering pump speeds for each desired volume in the test were 160, 280 and 400 rpm at low, middle and high pump settings, respectively. The volume of each fluid dispensed by the metering pump was measured with a scaled cylinder. Each test combination was repeated five times.

After the accuracy verification, the metering pump was calibrated to establish the relationship between the flow rate and input voltage. Tap water, turpentine oil, prime oil and sucrose solutions were used for the calibration. DC voltage signals were applied to the step motor controller board and variations of the voltages linearly manipulated the motor speeds to provide desired outputs. To calibrate the fluid metering pump, 16 voltages in the range of 0 to 2.510 V with 0.157 V intervals were selected to measure the flow rates dispensed from the metering pump. The step motor controller board could respond to this voltage input range and achieve 0 to 640 rpm speed with 40 rpm interval.

2.4. Mixture uniformity evaluation

To obtain desired mixture ratios before the spray mixture was delivered to the variable-rate nozzles, the pesticide mixing process in the in-line injection system should be designed properly to ensure uniform dilution of concentrated chemicals in the carrier (Lammers and Vondricka, 2010). For each viscous sucrose solution as a simulated pesticide, the mixture uniformity was evaluated with four ratios between the amount of the simulated pesticide dispensed from the metering pump and the amount of water discharged from the water pump. These ratios were 0.1%, 0.5%, 1.0%, and 2.0%. Tape water without any sucrose solution was also used as a simulated pesticide for control. Therefore, there were 20 treatments in the mixture uniformity evaluation tests [(water + 4 sucrose solutions) × 4 ratios = 20].

A fluorescence tracer Brilliant Sulfaflavine (BSF) (MP Biomedicals, Inc., Aurora, Ohio, USA) was added into each sucrose solution to quantify the ratio of the sucrose solution in water after they were mixed in the static mixer and transferred into the buffer tank. The BSF tracer had advantages of high sensitivity with relatively low cost and user safety compared with pesticides (Nuyttens et al., 2007; Jeon et al., 2011; Jeon and Zhu, 2012). The concentration of BSF in each sucrose solution was 4,000 μg mL^{-1} for the tests with ratios of 0.1%, 0.5% and 1.0%, and was 2,000 μg mL^{-1} for the tests with the 2.0% ratio. With this test design, the final BSF concentrations in each spray mixture in the buffer tank were supposed to be 4, 20, 40, and 20 μg mL^{-1} for the ratios of 0.1%, 0.5%, 1.0%, and 2.0%, respectively. These concentrations fell within the detection range of the fluorescent intensity based on pre-trials with the fluorometer (Turner Designs, Inc., Sunnyvale, California, USA) used for the tests.

As shown in Fig. 5, samples for the spray mixture containing each sucrose solution were collected from outlet of the buffer tank with thirty 120-mL glass bottles in sequence. It took about 1 s to fill each bottle, so about 30 s were required to complete the test for each ratio of the sucrose solution. Samples of mixture were randomly collected from different stages of dispensing cycles, including early and later stages and between two dispensing cycles. Each dispensing cycle was 45 s. After mixture samples were collected, they were transferred to 4 mL square cuvettes for fluorescence intensity analysis using the fluorimeter. The BSF tracer concentration (μg mL^{-1}) of the mixture as a function of fluorescence intensity was calibrated before the tests.

3. Results and discussion

3.1. Metering pump accuracy

The metering pump accuracy tests showed that the measured volumes of simulated pesticides (tap water, turpentine oil, and prime oil) were consistent with their desired volumes of 10, 50, 100, 200 and 300 mL for metering pump speeds of 160, 280 and 400 rpm, respectively (table 1). Greater relative errors and coefficients of variation were found when dispensing lower volumes of simulated pesticides at

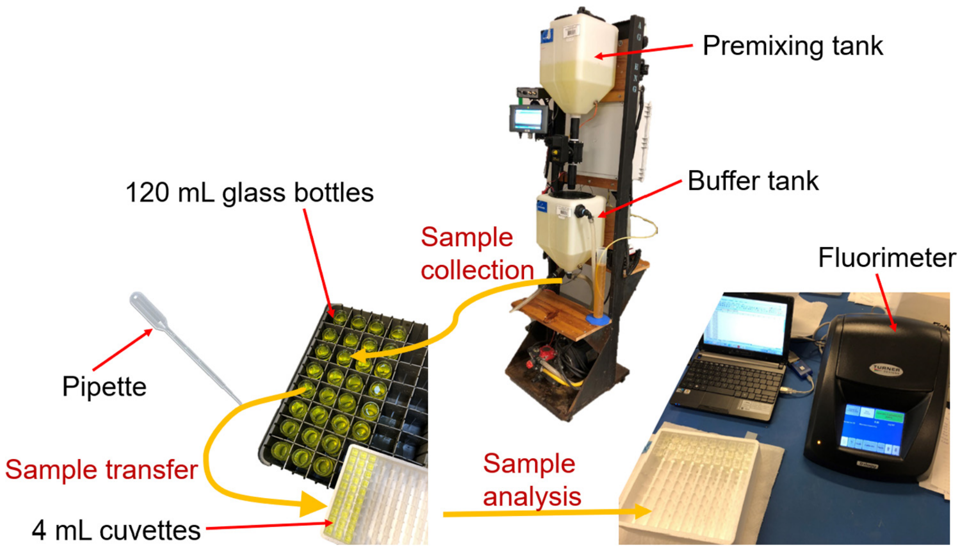

Fig. 5. Process of collection and analysis of buffer tank mixture samples for the mixture uniformity evaluation.

higher speeds. For example, the largest relative error and coefficient of variation (22%, 10.7% respectively) occurred when dispensing 10 mL prime oil at 400 rpm. However, when the volume was greater than or equal to 50 mL, high accuracy for all speeds and different simulated pesticides could be achieved. Similar results were presented for sucrose solutions with viscosities of 8.0, 16.0, 24.0 and 32.0 mPa·s (table 2). For example, the largest relative error (12%) occurred when pumping 10 mL sucrose solution with a viscosity of 8 mPa·s at 400 rpm. The largest coefficient of variation (5.8%) occurred at 280 and 400 rpm for dispensing the10 mL sucrose solution with a viscosity of 24 and 32 mPa·s, respectively.

At low pump speed (160 rpm), the metering pump was capable of dispensing relatively low volume of fluid with high accuracy. However, when the volume increased to a certain point, although the metering pump accuracy was still high, it would require long time to dispense that desired volume. In this case, the metering pump would not catch up the water pump discharge speed, which could result in the chemical concentrates injected into the static mixer without any water carrier before reaching the premixing tank. For example, it would require 76.2 s for the metering pump at 160 rpm to dispense 100 mL of fluid which was much longer than the time required for discharge 10 L of water from the water pump. To solve this problem, higher metering pump speeds were needed. However, as mentioned above, the accuracy of the pump decreased as the pump speed increased for dispensing liquid volume less than 50 mL. For example, the relative error reached as high as 12% to dispense 10 mL of liquid at the 400 rpm speed (Table 2).

Thus, to comply the metering pump accuracy with different settings, the metering pump speed was set at 160 rpm for low pesticide-to-water ratios (< 0.1%), 280 rpm at middle ratios (between 0.1% and 1.0%), and 400 rpm for high ratios (≥ 1.0%). The metering pump speeds were automatically selected and assigned through the Arduino encoded program to match the ratio ranges. In this way, the relative errors between measured volume and desired volume for different simulated pesticides could be controlled within less than 5% range, resulting in an acceptable accuracy for dispensing a wide range of metering volume.

3.2. Metering pump settings

With the automatic selection of metering pump speeds to dispense the desired volume of chemical concentrates within the 5% relative error range, regression analysis of test data showed that the relationship between input voltage and dispensed chemical flow rate for the metering pump could be expressed by a linear regression equation as,

$$y = 146.84x - 14.31,\ R^2 = 0.9996 \tag{1}$$

where x is the input voltage (V), and y is the dispensed chemical flow rate (mL min^{-1}).

The linear range started from very small detectable voltage input to an upper limit that was dependent upon the properties of the fluids. Within the linear range, the flow rate was directly proportional to the

Table 1
Measured volume (MV) along with relative error (RE) and coefficient of variation (CV) for water, turpentine oil, and prime oil as simulated pesticide concentrates at different metering pump speeds when desired volumes were 10, 50, 100, 200 and 300 mL.

Metering pumpspeed (rpm)	Simulated pesticide	Desired volume (mL)														
		10			50			100			200			300		
		MV (mL)	RE (%)	CV (%)	MV (mL)	RE (%)	CV (%)	MV (mL)	RE (%)	CV (%)	MV (mL)	RE (%)	CV (%)	MV (mL)	RE (%)	CV (%)
160	Water	10.2	2.0	4.4	49.4	1.2	1.8	99.8	0.2	1.5	197.0	1.5	0.9	297	1.0	0.9
	Turpentine	10.2	2.0	8.2	50.4	0.8	2.3	100.0	0	2.0	198.4	0.8	0.8	296	1.3	0.7
	Prime oil	9.6	4.0	5.7	49.4	1.2	2.7	98.8	1.2	1.1	198.4	0.8	0.8	296	1.3	0.8
280	Water	9.8	2.0	4.6	52.0	4.0	1.4	101.4	1.4	0.9	198.8	0.6	0.6	299	0.3	0.7
	Turpentine	8.4	16.0	6.5	49.6	0.8	3.4	100.0	0	1.4	199.2	0.4	0.5	298	0.7	0.8
	Prime oil	8.4	16.0	6.5	49.2	1.6	3.6	99.6	0.4	1.7	197.6	1.2	0.8	296	1.3	0.8
400	Water	9.6	4.0	5.7	50.4	0.8	1.8	101.8	1.8	1.1	201.8	0.9	0.5	308	2.7	0.9
	Turpentine	9.2	8.0	9.1	50.6	1.2	1.8	101.8	1.8	1.1	202.0	1.0	0.6	306	2.0	1.4
	Prime oil	7.8	22.0	10.7	51.6	3.2	3.2	101.2	1.2	2.3	202.6	1.3	0.8	307	2.3	0.9

Table 2
Measured volume (MV) along with relative error (RE) and coefficient of variation (CV) for sucrose solutions as simulated pesticide concentrates with viscosities of 8, 16, 24 and 32 mPa·s at different metering pump speeds when desired volumes were 10, 50, 100, 200 and 300 mL.

Metering pumpspeed (rpm)	Viscosity (mPa·s)	Desired volume (mL)														
		10			50			100			200			300		
		MV (mL)	RE (%)	CV (%)	MV (mL)	RE (%)	CV (%)	MV (mL)	RE (%)	CV (%)	MV (mL)	RE (%)	CV (%)	MV (mL)	RE (%)	CV (%)
160	8	9.6	4.0	5.7	48.2	3.6	0.9	98.2	1.8	0.5	195.2	2.4	0.4	298.0	0.7	0.9
	16	9.6	4.0	5.7	48.6	2.8	1.1	99.8	0.2	0.4	193.2	3.4	1.2	293.0	2.3	1.5
	24	9.8	1.7	4.5	48.8	2.3	1.1	98.7	1.3	0.9	194.3	2.8	1.2	290.8	3.1	0.8
	32	9.6	4.0	5.7	48.8	2.3	1.1	97.5	2.5	1.0	194.7	2.7	0.5	290.8	3.1	0.8
280	8	9.8	2.0	4.6	48.2	3.6	0.9	99.6	0.4	0.9	199.0	0.5	1.1	296.0	1.3	0.8
	16	9.6	4.0	5.7	49.6	0.8	1.1	98.8	1.2	0.5	198.4	0.8	0.5	298.0	0.7	0.9
	24	9.4	6.0	5.8	50.2	0.4	1.7	98.8	1.2	0.5	199.0	0.5	0.5	299.0	0.3	0.7
	32	9.4	6.0	5.8	49.2	1.6	0.9	99.6	0.4	0.5	199.6	0.2	0.4	296.0	1.3	0.8
400	8	8.8	12.0	5.1	49.4	1.2	1.1	99.6	0.4	1.1	200.4	0.2	0.4	301.0	0.3	0.7
	16	9.2	8.0	4.9	50.4	0.8	1.1	100.2	0.2	0.8	201.6	0.8	0.4	301.0	0.3	0.7
	24	9.4	6.0	5.8	49.0	2.0	2.0	100.2	0.2	0.4	201.2	0.6	0.5	301.0	0.3	0.7
	32	9.4	6.0	5.8	50.4	0.8	1.8	101.2	1.2	1.1	202.0	1.0	0.7	301.0	0.3	0.7

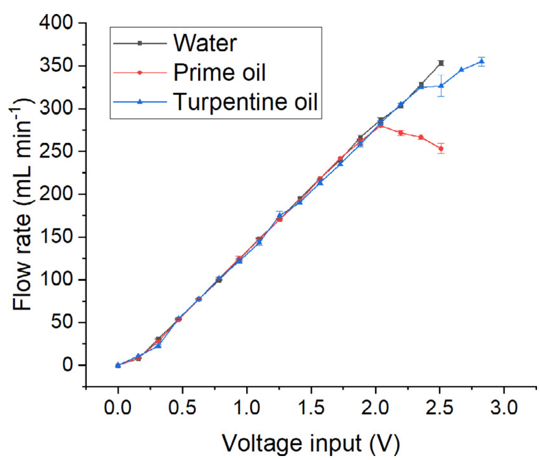

Fig. 6. Calibration curve of metering pump flow rates with various voltage inputs.

voltage input. For certain type of fluids if the flow rate did not increase in direct proportion to the voltage input, or if the flow rate decreased inversely, the voltage input could reach beyond the linear range. As shown in Fig. 6, for prime oil and turpentine oil, a non-linear relationship behavior was observed at the high voltage inputs (≥2.0 V), where the flow rate did not increase linearly as the voltage input. In the non-linear region, the change of the output was not proportional to the change of the input. Hence, the non-linear region could not be used as the working range and was removed from Eq. (1). Within the linear ranges for the input voltage between 0 and 1.8 V and the chemical flow rate between 0 and 250 mL min^{-1}, the slopes in the linear regression equations could accurately represent the magnitude of the increase in the flow rate with the increase in the voltage input.

The coefficient of Pearson correlation between water and prime oil was 0.9998, and was 0.9989 between water and turpentine oil. That is, the strength of the linear relationship between the dispensed chemical flow rate and voltage input was very strong regardless of fluid viscosities. Hence, it is reasonable to apply the metering pump calibration model of water presented in Eq. (1) to represent different types of fluids such as turpentine oil, prime oil and other fluids that were used to simulate pesticides with the similar viscosity range.

3.3. Mixture uniformity

The relationship between the BSF tracer concentration and fluorescence intensity could be determined by the following calibration equation,

$$y = (1.68 \times 10^{-4})x + 0.31, \ R^2 = 0.9988 \quad (2)$$

where y is the BSF tracer concentration (μg mL^{-1}), and x is the corresponding fluorescence intensity of the solution ($176 < x < 1.86 \times 10^5$).

The mixture ratio was defined as the chemical concentrate volume divided by the water volume. The ratio of the sucrose solution in the spray mixture for the samples collected at the buffer tank outlet was calculated from the measured BSF tracer ratio (y). To achieve a fluorescent intensity that fell within the linear range of the fluorimeter used for the test, Eq. (3) was used when the desired sucrose solution ratios in the spray mixtures were 0.1%, 0.5%, and 1.0%, respectively. However, Eq. (4) was used when the desired sucrose solution ratio in the spray mixture was 2.0%.

$$z = \frac{100 \bullet y}{4000 - y} \quad (3)$$

$$z = \frac{100 \bullet y}{2000 - y} \quad (4)$$

where z is the measured mixture ratio (%).

As shown in Fig. 7, except for slight fluctuations at high ratios, the ratio of simulated pesticides of various viscosities remained stable and consistent with very little variations over the 30 s sampling duration. That is, the uniformity of simulated pesticides in the buffer tank at lower ratios were more consistent than higher ratios.

For tap water and sucrose solutions with viscosities ranging from 0.9 to 32.0 mPa·s, the measured spray mixture ratios collected from the buffer tank was consistent with the desired ratios of 0.1%, 0.5%, 1.0% and 2.0% (Table 3). Among the solutions with 0.9, 8, 16, 24, and 32 mPa·s viscosities, the highest relative errors of the measured ratios were 4.0%, 7.6%, 6.7%, 6.1% and 5.8%, and the highest coefficient of variation were 3.5%, 1.1%, 2.9%, 2.9% and 4.5%, respectively. Generally, flow rates discharged from conventional pumps decreased as the viscosity increased due to additional resistances created from the viscus fluids to the pump. Differently from the conventional pumps, the metering pump used in this study had high accuracy and was carefully calibrated. The flow rate of simulated pesticides dispensed from the metering pump only fluctuated and decreased slightly from 218.3 to 213.3 mL min^{-1} as the viscosity increased from 0.9 to 32.0 mPa·s. Compared to the magnitude of these flow rates, this 2.3% change in the flow rates was negligible. Therefore, the flow rate of the metering pump was unaffected by viscous fluids within the specific viscosity range. For

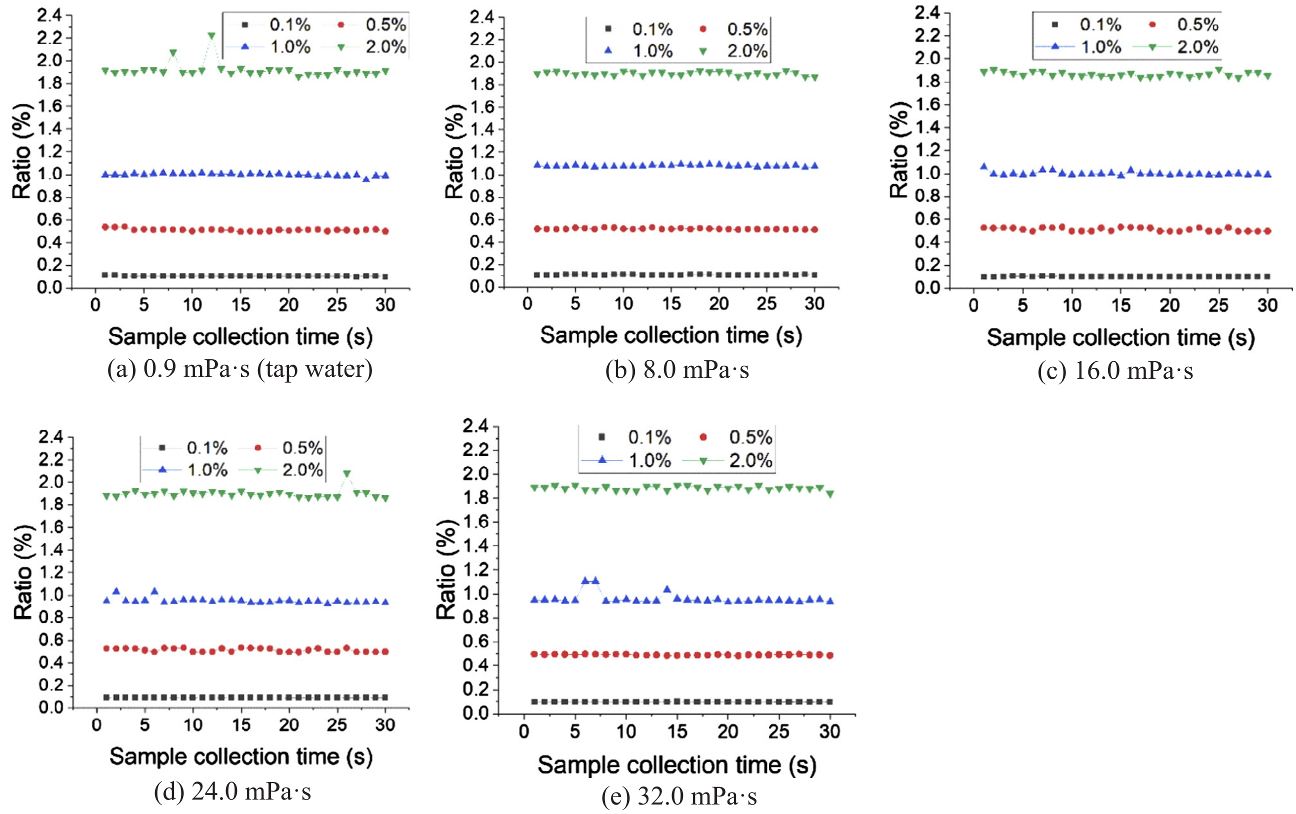

Fig. 7. Measured ratios for water-only and four sucrose solutions as five different viscous simulated pesticide concentrates in spray mixtures collected from the buffer tank when the desired ratios between the amounts of each sucrose solution and water in the buffer tank were 0.1%, 0.5%, 1.0% and 2.0%. Viscosities of water-only and four sucrose solutions were 0.9, 8.0, 16.0, 24.0, and 32.0 mPa·s, respectively.

spray mixtures containing 0.1–2.0% simulated chemical concentrates, the premixing in-line injection system provided consistent mixing uniformity. The relative errors were under 7.6%, and the coefficient of variations were under 4.5%.

In industrial applications, tank mixtures within 5% coefficient of variation in the uniformity distributions are considered as well-mixed homogenous mixtures (Paul et al., 2004). This industrial standard could be used to define the acceptable coefficient of variation for the agricultural direct in-line injection systems (Lammers and Vondricka, 2010). Also, less than 15% deviation in homogeneity of tank mixtures is considered as an acceptable variation for conventional sprayers (Balsari and Wehmann, 2015). Therefore, the premixing in-line injection system was able to provide uniform spray mixtures to meet the industrial standard and exceeded the acceptable uniformity level required for conventional spray systems.

4. Conclusions

An improved experimental automatic premixing in-line injection system controlled with an Arduino platform was developed to minimize the tank mixture leftover problem associated with variable-rate orchard sprayers. Test results demonstrated that the fluid metering pump could accurately dispense desired volume (up to 300 mL) of simulated pesticides with flow rates between 0 and 250 mL min^{-1} at different speeds, and the relative error between measured and desired volume could be controlled under 5%.

The premixing in-line injection system provided consistent mixing uniformity of spray mixtures containing 0.1% to 2.0% simulated chemical concentrates, and the relative error and coefficient of variation were under 7.6% and 4.5%, respectively. The measured spray mixture ratios collected from the buffer tank outlet agreed well with the desired

Table 3
Measured ratio (MC) along with relative error (RE) and coefficient of efficient (CV) for sucrose solutions of 8, 16, 24, and 32 mPa·s viscosities as the simulated pesticide concentrates in spray mixtures collected from the buffer tank when the desired ratios between the amounts of each sucrose solution and water in the buffer tank were 0.1%, 0.5%, 1.0% and 2.0%.

Viscosity (mPa·s)	Desired ratio between amounts of sucrose and water											
	0.1%			0.5%			1%			2%		
	MV (mL)	RE (%)	CV (%)	MV (mL)	RE (%)	CV (%)	MV (mL)	RE (%)	CV (%)	MV (mL)	RE (%)	CV (%)
0.9[a]	0.101	1.0	2.6	0.510	2.1	2.1	0.998	0.2	1.2	1.921	4.0	3.5
8	0.106	6.4	0.9	0.517	3.5	1.1	1.076	7.6	0.6	1.900	5.0	0.8
16	0.101	0.8	1.0	0.512	2.4	2.9	0.998	0.2	1.5	1.865	6.7	1.1
24	0.094	6.1	0.6	0.512	2.4	2.9	0.949	5.1	2.5	1.899	5.1	2.0
32	0.097	3.0	0.7	0.491	1.7	0.8	0.958	4.2	4.5	1.884	5.8	0.9

[a] Water-only as the simulated pesticide concentrate.

ratios even though they fluctuated and decreased slightly in an acceptable level as the viscosity increased.

Future investigations would include feasibilities to integrate the premixing in-line injection system into variable-rate orchard spraying systems for spray performance assessments.

Acknowledgments

Mention of company or trade names is for description only and does not imply endorsement by the USDA. The USDA is an equal opportunity provider and employer. The authors acknowledge invaluable technical assistance from Adam Clark, Barry Nudd, Andy Doklovic and Greg Smith. We are also grateful to the USDA-NIFA Specialty Crop Research Initiative (Grant No. 2015-51181-24253) for funding this research.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compag.2019.04.023.

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