Journal of Agricultural Engineering

Journal of Agricultural Engineering 2026; LVII:1912
doi:10.4081/jae.2025.1912

Design and effectiveness of an injection system for the application of liquid manure (slurry) to soil

Laleh Ghanizadeh Hesar,1 Ahmet Ince,1 Kamil Ekinci,[2] Huseyin Gucum[1]

[1]Department of Agriculture Machinery and Technologies Engineering, Cukurova University, Adana; [2]Department of Agricultural Machinery and Technology Engineering, Faculty of Agriculture, Isparta University, Isparta, Turkey

Abstract

Liquid manure is a rich source of nutrients for crops, but when applied by traditional methods (broadcast) it causes loss of important nutrients such as nitrogen by evaporation and leaching simultaneously causes environmental and groundwater pollution. In this study, a high-performance liquid manure injection tool (prototype) was designed, developed and evaluated under actual field conditions. The prototype injection system consists of a prototype liquid distributor wheel that injects the liquid subsurface at certain amounts and intervals without cultivating the soil. Since the liquid manure is injected subsurface, so does not remain on the soil surface, it does not need to be mixed, and alternative to other methods in terms of nitrogen loss and availability to the plant. Laboratory and field studies were conducted to explore this system in liquid manure application. The range of slurry application rates was 4000-20000 L ha-1, at the base of system pressure and forward speed. The trials to determine efficiency of system, image analysis methods were used to quantify the percentage of the surface area covered with manure, and ammonia emission rate were determined by employing a wind tunnel and a dynamic chamber. The results showed that injecting slurry reduced NH3 emissions most effectively to 70% compared to the traditional surface spreading method. No statistically significant effect of manure application depth on ammonia emission was observed. The manure cover decreased at used by injection system. The machine demonstrated its performance by successfully injecting liquid manure into the soil and preventing nitrogen losses since the fertilizer had minimal contact with the air.

Key words: liquid manure applicator; point injection; nitrogen loss; wind tunnel; ammonia reducing; sustainable agriculture.

Correspondence: Laleh Ghanizadeh Hesar, Department of Agriculture Machinery and Technologies Engineering, Cukurova University, 01330 Adana, Turkey. E-mail: lale.ghanizadeh@yahoo.com

Introduction

At the beginning of the twentieth century, a paramount global challenge emerged, namely the inadequacy of food provision in light of a growing world population. The major goal of all the agricultural production is to obtain more efficiency from the unit area or mass by intensifying the use of inputs. Fertilization, as a critical component, plays a significant role in shaping the landscape of agricultural practices. In order to increase the plant's utilization rate of animal manure, to prevent the loss of nitrogen by evaporation, and to minimize some of its negative environmental effects, it is necessary to apply it under the soil in appropriate doses with suitable machines. This situation also creates an advantage for the widespread use of direct sowing methods, which are an important component of sustainable soil management and carried out without tillage. In Turkey, animal manure is largely applied either by spraying on the soil or applying liquid manure through an on-farm irrigation system. According to the results of many studies, it was reported that in all these applications, liquid fertilizers turn into harmful greenhouse gases and accelerate climate change, cause environmental pollution, and threaten human and animal health (FAOSTAT, 2021).

The cattle breeding and manure fertilization are activities leading to the emission of gases of environmental concern, such as ammonia (NH_3), and greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O). Furthermore, it was determined that 55.5% of CH_4 emissions and 77.6% of N_2O emissions, which are included in the total greenhouse gas emissions, originate from agricultural activities (Turkish Statistical Institute, 2016). Approximately 45% of the nitrogen applied in liquid manure is evaporated into the atmosphere (Phillips, 1998). Spreading of slurry on the surface can lead to high losses of ammonia (Smith *et al*., 2000). Many studies have focused on reducing ammonia loss in manure application, especially on liquid manure. It was reported that the odor emission was reduced by approximately 80% when the liquid manure was applied to the soil with a properly adjusted injection depth compared to surface applications (Pain *et al*., 1991). Injecting liquid manure directly into the ground is an application that can serve the purposes of the direct sowing system, which is one of the main approaches of sustainable agriculture systems. However, suitable machinery is needed to inject this type of fertilizer into the soil. It was reported that fertilization management and application techniques are among the most important problems of direct sowing methods (Baker and Saxton, 2007). Use of the fertilizer injection system was found to significantly improve mid-season lettuce plant growth and nitrogen uptake levels as compared to the conventional knife blade fertilizer applicator system. These results are thought to be due to more optimal placement of the fertilizer in the root zone (Siemens *et al*., 2011). The effect of using the injection method on the yield of no-till winter wheat showed an increase of around 12 percent in comparison with the knife fertilizer, and on the other hand, significant reductions in surface runoff nutrient losses have also been reported (Kushnak *et al*., 1992). According to Randall *et al*. (1997), the choice of N placement method markedly affected both yield and profitability. The point injection of urea ammonium nitrate (UAN) produced the greatest grain yield and returned the highest net profit per acre, while broadcast and band applications yielded lower returns. Furthermore, the injected application method demonstrated superior N uptake and recovery efficiency, indicating enhanced fertilizer utilization and reduced loss. The objective of this study was to design, construct, and evaluate the performance of a liquid manure (slurry) injection system for farmland applications. Specifically, the study aimed to assess the effectiveness of subsurface injection in minimizing ammonia (NH_3) emissions compared to conventional surface application methods, thereby contributing to improved nutrient retention, reduced environmental pollution, and enhanced compatibility with sustainable agricultural practices such as no-till farming.

Methods and Materials

Design injection wheel

This study involved the design, construction, and performance evaluation of a prototype liquid manure injection system into the soil. The basic design of the liquid manure injector was given by Iowa State University (Cady, 1990). This system, based on a circular array of spokes, is a tractor-pulled wheel device designed to meter and inject homogeneous liquid manure into the ground. Consisting of 12 hollow spikes attached to a rotatable wheel, the liquid manure flows from these spokes as the wheel rotates. This system injects fluid below the ground surface to disperse it into the soil. The diameter of the wheel is approximately 400 mm, each spoke is 100 mm in length, and the distance between separated depots around it is about 148 mm (Figure 1 a,b). The spoked wheel assembly comprises a hub portion and twelve Tygon tubes extending radially outward from the hub. Each Tygon tube is connected to spikes. The wheel disposes of 12 hollow spikes, the so-called spokes. The spoke-hollow rods penetrate the soil as the wheel turns. The mechanical hub control, situated at the center of the wheel, manages the deposition of fertilizer into the suitable spokes. The

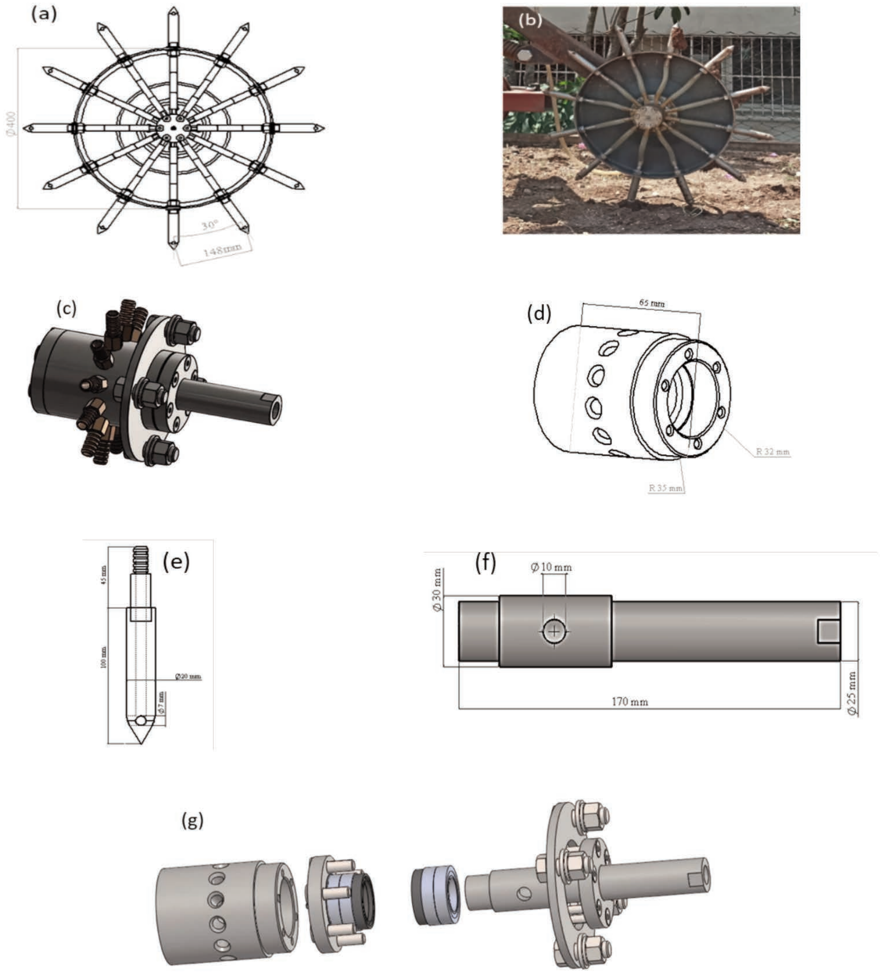

Figure 1. Liquid manure injector's wheel (**a,b**), mechanical hub (**c,d**), spoke (**e**), inner port of the mechanical hub (**f**) and view of hub assembly (**g**).

hub portion is formed of a housing having a bearing that is secured to permit rotational movement of the housing with respect to the axle (Figure 1 c,d). The fixed inner part (bearing) with a single hole and one outer part designed for rotation featuring 12 holes - the hub operates using a rotary valve. When these holes align with each spoke, which occurs only when the spoke is perpendicular to the ground, the system allows for liquid discharge. Injection is completed as the liquid manure enters the soil through two slits on the sides of each spoke (Figure 1 e,f). All parts of hub are assembled as shown in Figure 1g and placed in the center of the wheel.

Experimentation

Laboratory tests

For determination of injector wheel application rate and functionality, test setup was prepared in laboratory conditions. Experimental unit and replicates. The experimental unit was a depletion run of the injector system. For each combination of pressure (200, 300, 400, 500 kPa), simulated forward speed (1, 2, 3 km·h⁻¹), we performed n=6 independent runs, resetting the tank and re-pressurizing between runs. This experiment was conducted for two materials (liquid manure and water), completely independently of each other. The assembled wheel was fixed to a pedestal base. To supply the required liquid volume for the experiments, a small 20-liter tank was positioned directly beside the wheel. An air pressure regulator set (STNC- TL2000-2, TW5000-10 Air Filter Regulator), an air compressor (Sarmak compressor-pump-15/1005, 800 kPa) were used to control and maintain consistent air pressure within the tank during the trials. Forward speed was simulated using the 1.5 kW (2 hp) variable-speed DC Electric Motor. It was set to three different rotation speeds to conduct the experiments. The revolution of electric motor was adjusted by changing the voltage, accomplished with the aid of a VFD 2.2 kW variable frequency drive (inverter). The revolution was determined by using an axial shaft to connect the wheel to the electric motor (Figure 2). The speed of a motor was normally measured as the number of revolutions per minute (Sunil, 2020).

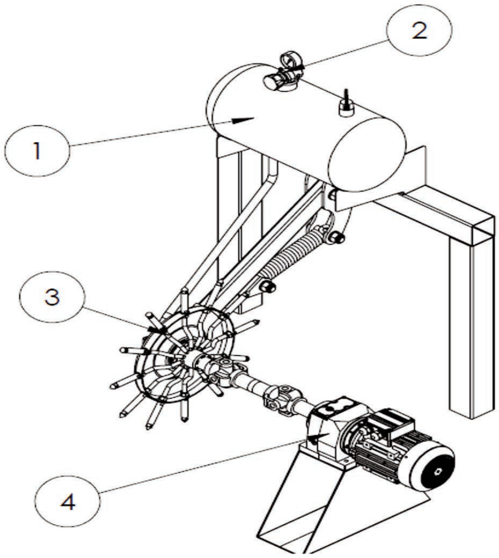

Figure 2. A view of the system installation for measurement application rate. 1, Tank; 2, pressure regulator; 3, injection wheel; 4, electric motor.

$$N = \frac{V\bar{x}60}{C} \qquad \text{(Eq. 1)}$$

The model (Eq. 1) describes the relative electric motor speed and tractor forward speed. The assumed tractor speeds in km h^{-1} were divided by 3.6 for converted to m s^{-1}, where C is the wheel perimeter (m), V is the tractor forward speed (m s^{-1}), N indicates revolutions per minute (rpm).

In the first case, the tank was filled with 5 L of liquid material out of 20-liter tank. It was pressurized for all four pressures considered in the experiment. Simultaneously, the injector wheel was rotated at each speed determined during the test program by an electric motor. This process was repeated for each experimental material (water and liquid manure). The time taken for the known volume (5 L) of liquid material to empty from the tank at different speeds and pressures was measured. Experiments were conducted in six repetitions, and the time required for the injection of the known volume was recorded (Figure 3). The application rate was calculated using Eq. (2).

$$N = \frac{600xQ}{VxB} \qquad \text{(Eq. 2)}$$

where N is the application rate (L ha^{-1}), Q is the flow (L min^{-1}), V is the tractor forward speed (km h^{-1}), and B is the working width (m).

Soil bin tests

The test was carried out on a soil bin channel with a length of 20 meters and a width of 2 meters to determine the efficiency and application rate of the system. Experiment arranged in a completely randomized design (CRD) at four different pressures (200, 300, 400 and 500 kPa) and at three different forward speeds (1, 2, and 3 km h^{-1}) with four replications.; the same carriage and injector were reused across treatments. The liquid manure was used as material. The injection wheel is a tractor-pulled equipment. The moving carriage on the rail system in the soil channel provided the movement

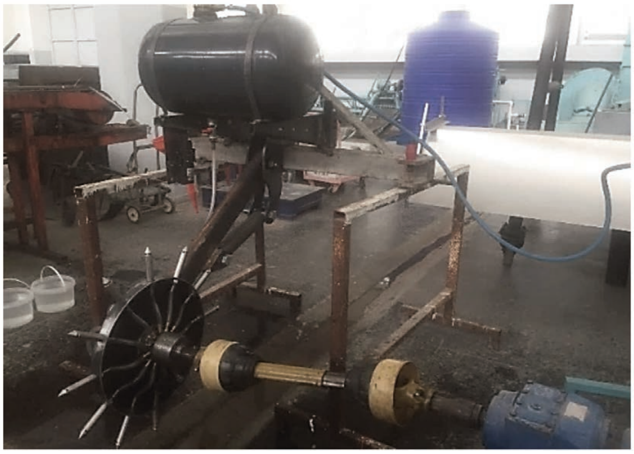

Figure 3. System setup in laboratory condition.

of the wheel. The desired forward speed was set by an inverter that was located at the moving carriage's main control console. An air pressure regulator set and air compressor were used to control and maintain air pressure consistency within the tank with a volume of 20 liters was mounted on the moving. carriage (Figure 4). Application rate was calculated at different pressures and forward speeds. For each repetition of the test, the tank was completely filled with test material (liquid manure). The decrease in the amount of liquid in the tank was determined after traveling a distance of 18 meters. This method was repeated for the desired speeds and pressures. Statistical analyses of data were conducted using SPSS 22, ANOVA was conducted to evaluate between-subjects effects.

Ammonia emission

Small wind tunnels (Lockyer, 1984; Hesar *et al*., 2024), which are used for ammonia volatilization from field soils, offer advantages of minimal environmental disturbance, study of several treatments, replication, measurement over larger areas, and the ability to make relative comparisons among treatments. In this study, the design and manufactured small wind tunnel were restricted by the housing and canopy section (Figures 5 and 6). A housing part with a cylindrical shape contains a sampling device, a fan for flowing air inside the tunnel, and flow meters. The housing part joined the U-shaped polycarbonate section of the tunnel that encloses a 1 m² treatment area (0.5×2.0 m) as the canopy section. In this section of the experiments, three wind tunnels were used to determine the effects of injection depth on ammonia emission. Experiments arranged in a randomized complete block design (RCBD), with repeated measures over 48 h. Treatments consisting of three methods and depths of fertilizer application (surface broadcast, 50 mm injection, and 100 mm injection) were applied in the soil bin and then the three tunnels were placed on them simultaneously. Ammonia emission measured in three wind tunnels. Sampling was carried out over a 48-h period, with measurements in the same experimental units being repeated three times for 48 h. Bovine slurry was used as the material, collected from the barn using a scraper and passed through the separator. The application rate was set at 85 kg ha^{-1} of total N (Wagner *et al*., 2021). In the traditional method, liquid manure (slurry) was sprinkled on the surface in a certain ratio, while in subsurface methods, it was injected using a point injection liquid manure system. Experiments included two application depths and comprised a surface broadcast application treatment. After the treatment areas were ready, the wind tunnels were placed in such a way that the canopies section covered the prepared treatments area. For each wind tunnel, the electric fan, a 25 cm diameter aluminum impeller with seven blades set at a 15 pitch to draw air across the enclosed area by velocity in the middle of the canopy at 1 m s^{-1} (Thompson *et al*., 1990). The star sampler device with eight legs was mounted in the cylinder section. Each leg extends 9 cm from a hollow hub that served as a vacuum manifold. The star sampler was connected to the gas scrubbing bottle. A small vacuum pump bubbled sampling air through this bottle (120 mL of boric acid) that traps the ammonia (Ozbek, 2017; Kumbul, 2023). The air flow rate through the acid traps was set at 5 L/min. The volume of air passing through the gas scrubbing bottles was measured with a gas-flow meter mounted in the entrance of the acid trap tube (Meisinger *et al*., 2001). Ammonia emission was quantified using an acid-trapping method in which volatilized NH_3 was absorbed in boric acid solution and subsequently quantified by titration. The experiments were conducted over a 48-h period, with air samples collected every 3 h. At each sampling interval, acid traps were replaced to maintain continuous collection efficiency. For each sampling point, boric acid solution containing mixed indicators (bromocresol green and methyl red) was used to capture volatilized ammonia. The absorbed ammonia was then titrated with a standard 0.5 N H_2SO_2 solution to determine the concentration of NH_3-N (Kumbul, 2023). The amount of ammonia emission was determined by quantifying the ammonia trapped in the acid and normalizing it to the surface area and exposure time. Accordingly, the daily ammonia volatilization flux (f, kg NH_3-N ha^{-2} day^{-1}) was calculated using Eq. (4), as described by Woodley *et al*. (2018):

$$c_a = \frac{(c_s \times v_s)}{v_a} \qquad \text{(Eq. 3)}$$

$$f = \frac{0.01(r \times c_a)}{A} \qquad \text{(Eq. 4)}$$

Figure 4. Installed Point Injection Liquid Manure System with small tank and air compressor on soil bin channel's moving carriage.

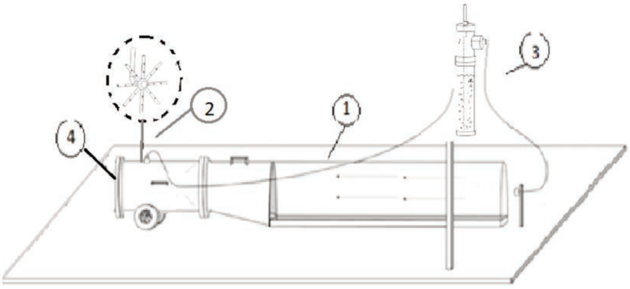

Figure 5. The side perspective of small wind tunnels. 1, Canopy covering; 2, air sampling section; 3, acid trap; 4, electric fan.

Figure 6. Small wind tunnel.

where c_a (mg $N.m^{-3}$) is the atmospheric concentration of NH_3-N at the wind tunnel, c_s (mg N L^{-1}) is the measured concentration of NH_3-N in the acid trap solution, v_s (L) is the measured volume of acid trap solution, v_a (m^3) is the measured volume of air passed through the acid trap solution, r (m^3 day^{-1}) is the air volumetric flow rate through the wind tunnel, and A (m^2) is the soil area covered by the wind tunnel. Statistical analyses of data were conducted using ANOVA (mixed-effects) to evaluate the effects of depth of injection liquid manure on ammonia emission, and *post-hoc* pairwise comparisons (Tukey's HSD) test were performed to examine the differences between the mean values.

Field test

Equipment

Observing the performance of the prototype model of the liquid manure applicator, an 8-row spoke wheel applicator prototype was designed and developed. The basic components of the machine were 8 sets of spoke wheels, a pump, a distributor, a fertilizer tank, and a pressure gauge (Figure 7).

The eight units of the spoke wheel liquid manure applicator, with a 5.6 m working width, were clamped on the toolbar at a uniform spacing of 700 mm between consecutive spoke wheels. A vacuum pump was used for the supply of liquid manure at constant pressure to the distribution hub. A control valve assembly was provided to regulate the pressure and bypass the extra quantity of liquid to the fertilizer tank with a maximum capacity of 7200 L min^{-1}. A mild steel tank having a capacity of 2000 L was used to store the liquid manure solution. Uniform distribution of liquid manure across the toolbar is important for ensuring proper application of manure nutrients to farm fields. For this aim, a custom-made distributor designed 32-liter cylinder with 8 wings fixed on the conical part inside it. The system lifted by the three-point hitch of a tractor (New Holland TD95d-70 kW).

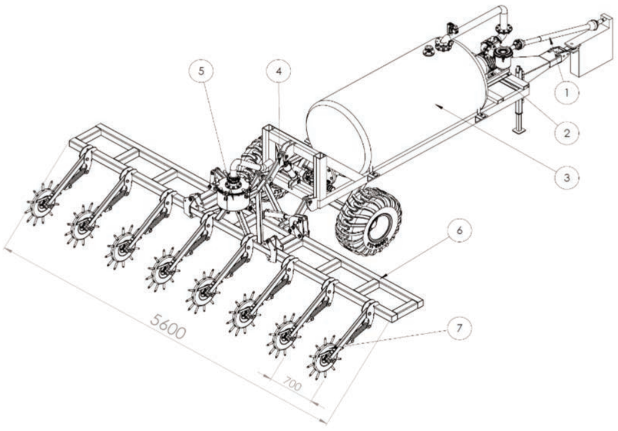

Figure 7. Side perspective of the injection machine. 1, Shaft; 2, pump; 3, fertilizer tank; 4, three-point hitch; 5, distributor; 6, main frame; 7, spoke wheel.

Experimental design

A field experiment was established to evaluate the efficiency of two liquid manure application methods in terms of ammonia losses and manure cover. The experimental site was divided into two whole plots, each measuring 5.6 m in width and 100 m in length. The whole-plot factor consisted of the manure application method, with one plot receiving liquid manure by injection and the other receiving manure by broadcast application. In the selected injection plot, the operating pressure of the pump was fixed at 200 kPa, and the machine was operated at a forward speed of 4 km h^{-1} in the field and 100 mm injection depth. At this operating pressure and forward speed, the machine delivers 4420 L·ha^{-1} of liquid manure. In order to compare the effectiveness of injection systems with surface application methods, the same rate of slurry was applied to another plot by broadcast application method. The tractor pulled the applicator that was fitted with flotation tires through a 100 m length for each of the plots (Figure 8).

Figure 8. Test of injection machine function and efficiency.

Ammonia emission

The experimental design follows a split-plot structure, employed 12 sets of dynamic chambers for each experiment plot. Within each whole plot, ammonia emissions were assessed by collecting twelve subsamples. After each test run, the amount of volatilized NH_3 was assessed under constant and controlled environmental conditions using dynamic chamber technique (Vandre and Kaupenjohann, 1998; Sommer *et al*., 2001). The closed cylinder method (dynamic chamber) utilized one-way open cylindrical plastic containers with a diameter of 200 mm and a height of 250 mm. Airflow was provided through the side holes. A vacuum pump was applied to flow air at a rate of 5 L min^{-1} to the 120 milliliters of boric acid trap (Figure 9). The trapped ammonia in boric acid samples was analyzed by acid titration using a predetermined sulfuric acid solution (McGinn and Janzen, 1998; Schlossberg *et al*.,

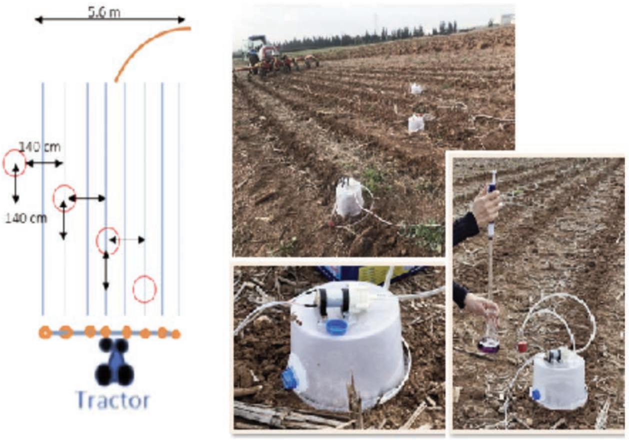

Figure 9. Ammonia emission measurement.

2017). The experiments ran for 6 hours, with samples collected every 2 h, and the ammonia emission flux was calculated in (mg m^{-2} day^{-1}). Results are given in percentage of nitrogen lost as ammonia with regard to the amount of total nitrogen spread with the slurry.

Liquid manure exposure

A large connected surface area between the air and the manure will result in more odors and ammonia being released. Both infiltration rate and contact area affect volatilization (Thompson *et al.*, 1990). Volatilization is increased when applying manure on a stubble or on straw residues on arable land (Amberger *et al.*, 1987). Due to decreased infiltration and an increased contact area. Following the manure injection, the image analysis (ImageJ) method was used to quantify the percentage of the surface area covered with manure (manure cover). To estimate the manure cover, a digital image (Figures 10 and 11) was quickly taken over the simple quadrants. The experimental design follows a split-plot structure. The experimental site, that was divided into two whole plots and with one plot receiving liquid manure by injection and the other receiving manure by broadcast application. Within each whole plot twelve simple quadrants (700 mm wide by 915 mm long) were placed randomly immediately following the manure application subsamples. These subsamples represent the subplot level. Photo taken from simple quarters, the images were processed with the ImageJ software, and the percentage of the surface area covered with manure was determined. Statistical analyses of data were conducted using SPSS ANOVA/Duncan analysis was conducted to evaluate the effects of application method of liquid manure on ammonia emissions. Duncan's multiple range tests were performed to examine the differences between the mean values.

Statistical analysis

Data from all trials performed and averaged data were checked for normality and constant variance using SPSS (22). Data from each trial were then subjected to analysis of variance (ANOVA), to assess treatment effects. Treatments were determined to be significantly different at α critical =0.05 and 0.01

Results and Discussions

Application rate

The application rate of liquid manure increased with higher operating pressure and decreased with increasing forward speed (Table 1). At 1 km h^{-1} and 500 kPa, the maximum application rate (20,776 L ha^{-1}) was observed, while the lowest rate (4110 L ha^{-1}) occurred at 3 km h^{-1} and 200 kPa. Factors affecting the amount of slurry to be applied are total N and nutrient value of slurry, method of liquid manure collection and storage, time and method of application, soil characteristics, type of crop which the slurry was applied, and climate. Several studies have evaluated the application rate of cattle slurry in farmland. In most European countries, recommendations on manure application rates are based on the total N applied per year the Code of Good Agricultural Practice applied in England recommends up to 250 kg N ha^{-1} yr^{-1} (Department for Environment, Food and Rural Affairs, 2009). However, mismanagement, such as a high application rate or inappropriate application time during the year, can lead to nutrient losses to the wider environment (Smith and Chambers,1993). The ANOVA confirmed that both forward speed and pressure had highly significant effects on application rate ($p<0.001$), and their interaction was also significant. Effect sizes were large (Partial η^2 >0.96), indicating that variations in forward speed and pressure strongly determined the applied manure volume (Table 2).

Effects of injection depth on ammonia emission

The results demonstrated that, in comparison to surface applications, Point Injection Liquid Manure Machines decreased N losses (Table 3). *Post-hoc* pairwise comparisons (Tukey's HSD) demonstrated that surface broadcast application resulted in significantly higher emissions than both 50 mm and 100 mm injection depths ($p<0.001$). However, emissions between the 50 mm and 100 mm injection treatments did not differ significantly ($p=0.176$), suggesting that both injection methods substantially reduced ammonia losses compared to surface application. Comparable outcomes were found in the literature. Given that injecting fertilizer would release ammonia (Baker *et al.*, 1989), they used a point injection system to apply chemical fertilizer at rates of 227 kg ha^{-1}

Table 1. Application rate (L ha^{-1}) at different forward speeds and operating pressures.

Forward speed (km h^{-1})	Pressure			
	200 kPa	300 kPa	400 kPa	500 kPa
1	12790.00	16360.00	18622.00	20776.00
2	6074.00	8020.00	9304.00	10366.00
3	4110.00	5384.00	6284.00	7194.00

Table 2. Results of the ANOVA (Tests of Between-Subjects Effects), forward speed, operating pressure, and their interaction.

Source	Square	df	Sig.	F	Partial η²
Corrected Model	2004046761.3*	11	0.000	7120.06	0.999
Forward speed (fs)	1701231566.3	1	0.000	33243.14	0.999
Pressure (P)	259973099.1	2	0.000	3386.69	0.994
Interaction (fs × P)	42842095.9	6	0.000	279.05	0.965

*Type III sum of squares.

for irrigating and 272 kg ha^{-1} for dryland. The machine's impact on nitrogen losses in comparison to surface application, which showed a loss of 3.63 kg ha^{-1} in the injected application and 26 kg ha^{-1} in the surface application. Another study found that ammonia losses were 16% and 27%, respectively, after medium-sized tubulators injected manure at an 8 cm depth and used a double disc tine (Rodhe *et al.*, 2004). The decreased NH_3 volatilization, on the other hand, indicates that there is more total ammoniacal nitrogen (TAN) available for plant uptake. During a five-year study, they found that precision-injected sludge had an impact on the average whole crop yield, grain yield, percentage of grain, percentage of dry matter, and uptake of N and P (Hunt and Bittman, 2021).

It is possible to draw the conclusion that NH_3 volatilization can be considerably decreased by slurry injection in soil in the current

Figure 10. Manure exposure by injection system (left) and manure exposure after image analysis (right).

Figure 11. Manure exposure by broadcast (left) and manure exposure after image analysis (right).

Table 3. Mean ammonia emission and results of repeated measures ANOVA and Tukey's HSD *post-hoc* test for different application depths.

Applications	Mean emission (kg NH_3-N ha^{-1} day^{-1})
Surface	3.0056^{a}
50 mm-subsurface	1.4662^{b}
100 mm-subsurface	0.7438b

Source	df	F	Sig. (p)
Depth (treatment)	2	38.78	<0.001 ***
Tunnel (block)	2	0.01	0.988 (ns)
Time	1	145.19	<0.001 ***
Depth × time	2	26.06	<0.001 ***
Error	136		

Comparison	Mean difference	p-value	
100 mm *vs* 50 mm	+0.72	0.176	ns
100 mm *vs* surface	+2.26	<0.001	***
50 mm *vs* surface	+1.54	<0.001	***

ns, not significant (p>0.05); ***p<0.001; [a,b]significant differences among treatments according to Tukey's HSD (p<0.05); values with the same letter are not significantly different.

Table 4. Effect of manure application technique on manure cover and ammonia loss under the same soil moisture, application rate, and TAN content.

Application technique	Soil moisture content (%)	TAN content (g kg^{-1})	Application rate (L ha^{-1})	Manure cover (%)	Volatilization (% of TAN applied)
Broadcast	28	3.5	4420	40.7^{a}	78.8^{a}
Injection	28	3.5	4420	2^{b}	12^{b}

TAN, total ammoniacal nitrogen (NH4+ + NH3); [a,b]significantly different at p<0.05 according to Duncan's multiple range test.

study. The highest ammonia flux was recorded in the treatment area, especially in the first few hours after the application (Figure 12). The results showed a highly significant main effect of application depth (F=38.78, $p<0.001$) and time (F=145.19, $p<0.001$) on ammonia emission. The interaction between depth and time was also significant (F=26.06, $p<0.001$), indicating that emission patterns differed depending on fertilizer application method. No significant differences were observed between wind tunnels ($p=0.99$), confirming that the block effect was negligible.

Notably, the surface application method recorded 12 kg NH_3-N ha^{-1} day^{-1} within the first three hours, whereas the 50 mm subsurface application and 100 mm subsurface application measured 4.82 kg NH_3-N ha^{-1} day^{-1} 1 and 3.84 kg NH_3-N ha^{-1} day^{-1}, respectively. Approximately 30% of ammonia emissions took place in the first three hours, 40% in the first six hours, and 50-60% in the first nine hours (Figure 12). Ammonia volatilization was measured using a small wind tunnel over a 14-day period in a nitrogen balance study on a urea-fertilized pasture. It was found that while emission rates were high for the first 24 h, they quickly dropped to relatively low rates in the following 3-4 days (Vallis *et al*., 1982). Over 90 hours after applying cattle slurry to grassland, accumulated nitrogen losses were noted in another study as ammonia (Rodhe *et al*., 2004). After applying cattle slurry to grassland with tines, losses as ammonia were found to be approximately 60% within the first ten hours (Huijsmans and De Mol, 1999).

Field study

The field experiment demonstrated a clear difference between manure application methods in terms of both manure cover and ammonia volatilization. Statistical analysis revealed that application method had a significant effect on both manure cover and ammonia volatilization ($p<0.001$). Broadcast application resulted in a significantly greater manure cover 40.7% compared with injection 2.0% (Table 4). The manure cover was significantly affected by the application method. Reducing the manure surface area and minimized air circulation at the manure surface can be used to reduce emission (Doorn *et al*., 2002). The 22% manure cover was rated as poor injection tool performance by Hultgreen and Stock (1999).

The effect of the application techniques was analyzed by the percentage of volatilization. In comparison with surface spreading, injection of slurry may improve nitrogen utilization due to reduced ammonia volatilization. The highest rate of NH_3 fluxes were measured as broadcast application plot at first hours after applying. Similarly, ammonia volatilization losses were markedly higher under broadcast application (78.8% of TAN applied) than injection (12.0%). The application of liquid manure on the soil led to the highest recorded ammonia emission levels, marking an approximate 70% increase compared to the injection of manure at a depth of 100 mm. According to Duncan's multiple range test, treatments were separated into two distinct groups (a, b), confirming the strong advantage of injection in reducing surface exposure and ammonia losses (Table 4).

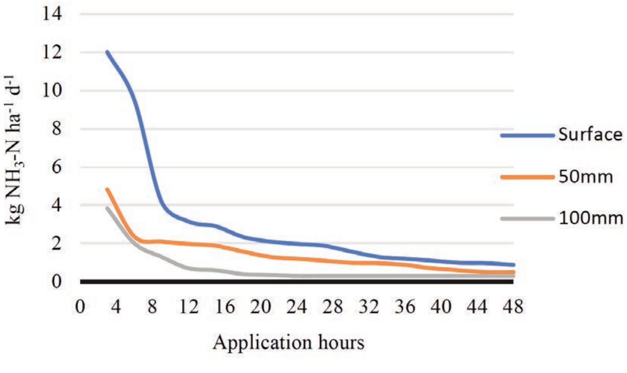

Figure 12. The outcomes of polynomial regression analyses characterizing ammonia emission across various treatment methods.

Conclusions

The surface application of liquid manure typically results in up to 90% ammonia nitrogen loss by evaporation, which presents significant environmental and financial difficulties. The results showed that injected manure has been found to result in significantly less N losses. In this study a specialized liquid manure/fertilizer system, called the point injection liquid manure system, was designed and constructed. It can effectively inject liquid fertilizer up to 100 mm deep below the soil surface at intervals of 140 mm and regulating fertilizer quantity, permitting application rates ranging from 4000 to 20,000 L ha^{-1}, adaptable to changes in working speeds and pressure. Further field studies demonstrated that the machine injected the necessary flow rate and that the speed and pressure of the machine could be adjusted to alter this rate.

As a result of the data and observations obtained in the study, it was concluded that liquid fertilizer application machines with prototype injection wheels can minimize nitrogen losses by injecting the liquid to the desired depth, facilitating the uptake of nutrients in the fertilizer by the plant and help reduce environmental pollution. The substantial 70% decrease in nitrogen loss between the injected and surface application (broadcast) methods stands out as a crucial indicator of the increased soil nitrogen retention. By injecting the fertilizer into the soil without processing it and reducing its interaction with the air, this technology may be a strong contender for sustainable agriculture, as studies have shown that the highest ammonia losses occur within the first hour following application. Future studies should focus on the evaluation of economic and environmental benefits of point injection system, along with the other placement options such as precision agriculture, applications in row-based and distribution of pesticides or low-dosage chemical manures.

References

Amberger A, Huber J, Rank M, 1987. [Gülleausbringung: Vorsicht, Ammoniakverluste].[in German]. DLG Mitteilung 102. Frankfurt, DLG e.V.

Baker CJ, Saxton KE, 2007. No-tillage seeding in conservation agriculture. Rome, FAO and CABI Publishing.

Baker JL, Colvin TS, Marley SJ, Dawelbeit ML, 1989. A point-injector applicator to improve fertilizer management. Appl Eng Agric 5:334-338.

Cady WF, 1990. Spoked wheel fertilizer injector. U.S. Patent US 4919060A.

Department for Environment, Food and Rural Affairs, 2009. Protecting our water, soil and air: a code of good agricultural practice for farmers, growers and land managers. Available from: https://assets.publishing.service.gov.uk/media/

5a7cbb27ed915d6822362336/pb13558-cogap-131223.pdf

Doorn MRJ, Natschke DF, Thorneloe SA, Southerland J, 2002. Development of an emission factor for ammonia emissions from US swine farms based on field tests and application of a mass balance method. Atmos Environ 36:5619–5625.

FAOSTAT, 2021. FAOSTAT Online Database. Food and agriculture data. Available from: https://www.fao.org/faostat/en/#home

Hesar LG, İnce A, Ekinci K, Gücüm H, Vurarak Y, 2024. Construction and evaluation of the wind tunnel technique for estimating ammonia volatilization from land. BIO Web Conf 85:01075.

Huijsmans JFM, De Mol RM, 1999. A model for ammonia volatilization after surface application and subsequent incorporation of manure on arable land. J Agric Eng Res 74:73-82.

Hultgreen G, Stock W, 1999. Injecting swine manure with minimum disturbance. Proc. Workshop on Soils and Crops. Available from: https://harvest.usask.ca/server/api/core/bitstreams/508a6bb6-918c-4d25-8572-494df561a691/content

Hunt DE, Bittman S, 2021. Precision injection of dairy sludge on crop yield and N and P uptake in juvenile and mature no-till silage corn. Agronomy 11:370.

Kumbul BS, 2023. Effects of different biochar applications on usable compost production in organic farming. Ph.D. Dissertation, University of Applied Sciences, Isparta.

Kushnak GD, Jackson GD, Berg RK, Carlson GR, 1992. Effect of nitrogen and nitrogen placement on no□till small grains: plant yield relationships. Commun Soil Sci Plant Anal 23:2437-2449.

Lockyer DR, 1984. A system for the measurement in the field of losses of ammonia through volatilisation. J Sci Food Agric 35:837-848.

McGinn SM, Janzen HH, 1998. Ammonia sources in agriculture and their measurement. Can J Soil Sci 78:139–148.

Meisinger JJ, Lefcourt AM, Thompson RB, 2001. Construction and validation of small mobile wind tunnels for studying ammonia volatilization. Appl Eng Agric 17:375-382.

Özbek O, Konak M, 2017. Effect on ammonia losses of different applicators on liquid manure distribution machines. Selcuk J Agric Food Sci 31:1-10.

Pain BF, Phillips VR, Huijsmans JFM, 1991. Anglo-Dutch experiments on odour and ammonia emissions following the spreading of piggery wastes on arable land. IMAG Report No. 91-9.

Phillips R, 1998. Gaseous emission from the different stages of European livestock farming. In: T. Matsunaka (ed.), Proc. Int. Workshop on Environmentally Friendly Management of Farm Animal Waste; pp. 67–72.

Randall GW, Iragavarapu TK, Bock BR, 1997. Nitrogen application methods and timing for corn after soybean in a ridge□tillage system. J Prod Agric 10:300–307.

Rodhe L, Rydberg T, Gebresenbet G, 2004. The influence of shallow injector design on ammonia emissions and draught requirement under different soil conditions. Biosyst Eng 89:237-251.

Schlossberg MJ, McGraw BA, Hivner KR, Pruyne DT, 2017. Method for flux-chamber measurement of ammonia volatilization from putting greens foliarly fertilized by urea. Clean Soil Air Water 45:1700085.

Siemens MC, Nolte KD, Gayler RR, 2011. Improving lettuce production through utilization of spike wheel liquid injection systems. Proc. ASABE Ann. Int. Meet., Louisville, paper no. 1111245.

Smith KA, Chamber BJ, 1993. Utilizing the nitrogen content of organic manures on farms - problems and practical solutions. Soil Use Manage 9:105-111.

Smith KA, Jackson DR, Misselbrook TH, Pain BF Johnson RA, 2000. Reduction of ammonia emission by slurry application techniques. J Agric Eng Res 773:277–287.

Sommer SG, Sogaard HT, Møller HB, Morsing S, 2001. Ammonia volatilization from sows on grassland. Atmos. Environ. 35:2023-2032.

Sunil BS, 2020. Development of battery electric vehicle operated weeder. Doctoral dissertation. University Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola.

Sunil BS, 2020. Development of battery electric vehicle operated weeder. Doctoral dissertation. University Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola.

Thompson RB, Pain BF, Lockyer DR, 1990. Ammonia volatilization from cattle slurry following surface application to grassland: I. Influence of mechanical separation, changes in chemical composition during volatilization and the presence of the grass sward. Plant Soil 125:109–117.

Turkish Statistical Institute, 2016. Available from: http://www.tuik.gov.tr/

Vallis I, Harper LA, Catchpoole VR, Weier KL, 1982. Volatilization of ammonia from urine patches in a subtropical pasture. Aust J Agric Res 33:97-107.

Vandré R, Kaupenjohann M, 1998. In situ measurement of ammonia emissions from organic fertilizers in plot experiments. Soil Sci Soc Am J 62:467–473.

Wagner C, Nyord T, Vestergaard AV, Hafner SD, Pacholski AS, 2021. Acidification effects on in situ ammonia emissions and cereal yields depending on slurry type and application method. Agriculture 11:1053.

Woodley AL, Drury CF, Reynolds WD, Calder W, Yang XM, Oloya TO, 2018. Improved acid trap methodology for determining ammonia volatilization in wind tunnel experiments. Can J Soil Sci 98:193-199.

Received: 9 July 2025; Accepted: 27ovember 2025.

Contributions: all authors made a substantive intellectual contribution, read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

Conflict of interest: the authors declare no competing interests and all authors confirm accuracy.

Availability of data and materials: all data generated or analyzed during this study are included in this published article.