Hindawi
International Journal of Agronomy
Volume 2019, Article ID 9283106, 10 pages
https://doi.org/10.1155/2019/9283106

Research Article

Nitrogen Use Efficiency and Gaseous Nitrogen Losses from the Concentrated Liquid Fraction of Pig Slurries

G. L. Velthof and R. P. J. J. Rietra

Wageningen Environmental Research, Wageningen University & Research, P.O. Box 47, 6700 AA Wageningen, Netherlands

Correspondence should be addressed to R. P. J. J. Rietra; rene.rietra@wur.nl

Received 21 January 2019; Accepted 10 April 2019; Published 2 May 2019

Guest Editor: Stefania Pindozzi

Processed manure can be an alternative source of nutrients for untreated manure and mineral fertilizers. Mineral concentrates (MCs) are derived from reversed osmosis of the liquid fraction of separated pig slurries. The emissions of ammonia (NH_3) and nitrous oxide (N_2O) from different (processed) manures and fertilizers were tested in an incubation experiment and a greenhouse experiment with grass as a test crop. Dry matter yields and nitrogen (N) uptake were also determined in the greenhouse experiment. Incorporation into the soil decreased on NH_3 emission but increased N_2O emission for all nitrogen products (mineral fertilizer, untreated slurry, MC, and solid fraction of separated slurry). Incorporation of both MC, slurries, and mineral fertilizers increased N_2O emission in the incubation experiment. The lowest apparent N recovery (ANR) in the pot experiment with grass was obtained for incorporated pig slurry (30–39%) and surface-applied MC (33–38%), while the highest ANRs were obtained for liquid ammonium nitrate (45–53%) and acidified MC (43–55%). It is concluded that MCs have a similar N fertilizer value as mineral N fertilizers if NH_3 emission is reduced by incorporation or acidification.

1. Introduction

Livestock manure is a valuable source of nutrients for crops and organic matter for soil. However, high losses of nitrogen (N) and phosphorus (P) have caused environmental problems related to soil, water, and air quality in many regions with intensive livestock farming systems [1]. In the European Union, a series of environmental policies has been implemented to decrease N emissions [2]. Lower inputs by fertilizers and manures have decreased both nitrate (NO_3^-) leaching to ground and surface waters and gaseous emissions to the atmosphere as ammonia (NH_3) and nitrous oxide (N_2O) in the EU in 2000–2008 [3]. However, further improvements in manure management are needed to meet the environmental targets. Improved manure management based on high-technology manure processing and transport of processed manures from intensive livestock regions to regions with arable cropping systems is seen as an important measure to decrease nutrient losses to the environment and increase nutrient use efficiency in intensive livestock systems [4, 5].

Separation of livestock slurries into a liquid and a solid fraction may increase both the N and P use efficiencies of manure and decrease losses to the environment [6]. The liquid fraction contains most of the N and potassium (K) and the solid fraction contains P and organic matter, so that application rates of both fractions can be tuned to the crop demand for nutrients. However, the volume of the liquid fraction is large, so that transport from the liquid fraction is costly. Reverse osmosis is a technique by which water can be removed from salt solutions [7, 8]. Application of reverse osmosis to the liquid fraction of separated slurry allowed a volumetric liquid manure reduction of 30 to 77% [9–12]. A lower volume of manure decreases the transport cost and may be a solution to transport excess of N from regions with a high livestock density to regions with arable cropping systems.

Field tests with the concentrated liquid fraction derived from reverse osmosis (mineral concentrate (MC)) showed that the nitrogen fertilizer replacement value (NFRV) is about 72–84% on maize and potato compared to calcium ammonium nitrate (CAN) fertilizer [13, 14]. Field experiments on grassland showed an N efficiency of 75% on sand and 58% on clay soil using CAN as a reference [15, 16]. Compared with liquid ammonium nitrate as a reference, the N efficiency of MC was 89% on sand and 92% on clay. The lower N efficiency of liquid fraction compared to the mineral fertilizer is likely related to gaseous N losses, mainly as NH_3 [17]. Several studies showed a lower NH_3 emission after application of liquid fraction than after application of untreated slurry [18–21]. This is attributed to the lower dry matter content of the liquid fraction than of slurry, by which the NH_4^+ rapidly infiltrates into the soil and NH_3 emission is reduced. However, studies in which manure is incorporated in the soil often show that incorporation of N in the soil increases N_2O emission because the higher N and lower oxygen concentrations in the soil after incorporation promote N_2O production during nitrification and denitrification [22]. However, the presence of organic matter in untreated slurry may increase N_2O emission because available organic matter is an energy source for denitrifying bacteria and promotes oxygen consumption in soils [23]. Clearly, there is a need to get more insights into the risk of NH_3 and N_2O emissions and N efficiency of liquid fractions of processed livestock slurries in order to increase the N use efficiency of slurries and to decrease the negative environmental effects of the use of slurries.

An incubation experiment was carried out to determine the risk of NH_3 and N_2O emissions from MC in comparison to untreated slurries, solid fractions of pig slurry, and mineral N fertilizers. It was hypothesized that the NH_3 emission from MC was smaller than that from untreated pig slurries because the N in MC infiltrates more rapidly into the soil than the N in slurries. It was also hypothesized that the difference in N_2O emission between MC and untreated pig slurry is difficult to predict because many factors (and interactions between factors) affect the production of N_2O during nitrification and denitrification in the soil, e.g., the pH and the concentrations of N, C, and oxygen of soils.

The apparent N recovery (ANR) of MC and untreated pig slurries were determined and compared with mineral N fertilizers in a pot experiment with grass as a test crop. It was hypothesized that abatement of NH_3 emission by incorporation or acidification of MC increased the ANR of MC.

2. Materials and Methods

2.1. Incubation Experiments

2.1.1. Mineral Concentrates. The experiments were carried out with pig slurries, MC (produced by reversed osmosis of the liquid fraction of separated slurries), and sold fractions of separated slurries derived from four manure processing plants (A, B, C, and D) [12]. There was one plant in which the digestate of codigested pig slurry and maize residues was treated: plant A. The other plants (B, C, and D) treated raw pig slurry, which was not digested or codigested. The separation techniques differed between the four plants. Plant A was used as a centrifuge, plants B and C a belt press, and plant D a screw press to separate digestate or slurries into liquid and solid fractions. Plant A used ultrafiltration and the other plants used air flotation for further cleaning of the liquid fraction. Plant B added both a coagulant (iron(III) sulphate) and flocculant (polyacrylamide), and the plants C and D added only polyacrylamide to promote the cleaning of the liquid fraction. The osmotic pressure was 60, 70, 60, and 40 bar for plants A, B, C, and D. The composition of the untreated slurries, MC, and solid fractions is presented in Table 1.

2.1.2. Experiment with Arable Soil. An incubation experiment was carried out to quantify the NH_3 and N_2O emissions from surface-applied and incorporated fertilizers, slurries, and processed slurries. This experiment was carried out using a sandy soil from an experimental farm with an arable crop rotation (Rolde, The Netherlands, 52°57′N, 6°39′E). The organic matter content of the soil was 4.4%, pH-KCl 5.1, and total N 1.22 g·kg^{-1}. The soil was air-dried and sieved with a 10 mm sieve. The treatments included an unfertilized control, three mineral fertilizers with different types of N (calcium ammonium nitrate, urea, and urean, i.e., a liquid fertilizer containing urea and ammonium nitrate), four untreated pig slurries (A, B, C, and D), four solid fractions (derived from separation of slurries A, B, C, and D), and four MC (produced by reversed osmosis of the liquid fraction of separated slurries A, B, C, and D). The experiment was carried out for 2 application methods (surface application and incorporation), 16 treatments, and in 3 replicates. The incubation was conducted using bottles of 1 litre to which 600 g dry soil was added. The surface area of the soil in the bottles was 69.4 cm^2. After filling the bottles with dry soil, water was added to achieve moisture content below field capacity. Thereafter, the bottles with moist soil were preincubated for 1 week at 20°C to activate microorganisms in soil. Thereafter, fertilizers and manures were applied to the soils. The incubation experiment was carried out at 20°C. The soil was brought at gravimetric moisture contents similar to field capacity by adding water, taking the amount of water added with (treated) slurries into account. Field capacity is the moisture content of the soil after excess water has drained (generally, a few days after rainfall). The moisture content of the soil was kept stable until day 7 by weighing the bottles and adding water after each measurement. At day 7, water was added to simulate rainfall (7 mm). Rainfall is an important factor controlling N_2O emission because it enhances denitrification and the N_2O production during nitrification.

All fertilizers and slurries were both surface applied and incorporated and were applied at a rate equivalent to 170 kg·N per ha (the maximum amount for livestock manure of the Nitrates Directive of the European Union). The fluxes of NH_3 and N_2O were measured 12 times: ½, 1, 2, 4, 7, 8, 11, 14, 21, 22, 23, and 28 days after N application. The concentration of NH_3 and N_2O was measured using an

Table 1: Composition of the tested products (expressed on basis of fresh weight).

Experiment	Product[1]	Dry matter ($g{\cdot}kg^{-1}$)	N ($g{\cdot}N{\cdot}kg^{-1}$)	NH_4-N ($g{\cdot}N{\cdot}kg^{-1}$)	NH_4-N/total N	P ($g{\cdot}P{\cdot}kg^{-1}$)	pH
Incubation	Pig slurry A	92	7.7	4.8	0.62	1.8	8.2
	Pig slurry B	89	6.9	4.5	0.65	1.8	7.7
	Pig slurry C	84	6.8	4.5	0.66	1.7	7.3
	Pig slurry D1	92	5.3	2.9	0.54	2.7	7.5
	Average	89	6.7	4.2	0.62	2.0	7.7
	MC A	18	6.6	4.1	0.62	0.6	8.6
	MC B	46	7.7	7.4	0.96	0.0	7.7
	MC C	46	9.1	7.7	0.85	0.4	7.9
	MC D1	24	5.5	5.1	0.92	0.1	7.9
	Average	34	7.2	6.1	0.84	0.3	8.0
	Solid fraction A	272	11.1	6.2	0.56	6.7	n.a.[2]
	Solid fraction B	290	12.4	5.2	0.42	6.3	n.a.
	Solid fraction C	313	12.9	5.1	0.40	7.3	n.a.
	Solid fraction D1	259	11.1	4.4	0.39	7.5	8.2
	Average	284	11.9	5.2	0.44	7.0	8.2
Pot	Slurry D2	71	6.3	4.1	0.65	1.5	7.7
	MC D2	58	8.0	7.1	0.89	0.3	7.9

[1]The different manure treatment plants are indicated with A, B, C, and D. D1 (used in the incubation experiment) and D2 (used in the pot experiment) represent different sampling times at plant D. [2]n.a.: not analysed.

Innova 1312 photoacoustic gas analyser. At each measurement time, the bottles were closed with a stopper and the concentrations of NH_3 and N_2O were measured in the headspace directly after closing the bottle and after about 1 hour. Values were corrected for ambient N_2O concentration and for mixing of the sample with the gas of the previous measurement which was present in the analyser. The emission was calculated assuming a linear increase, as described in more detail in various studies [24, 25, 26]. However, the increase of NH_3 concentration in closed systems generally decreases in time because of the accumulation of NH_3 in the air in the headspace. Therefore, the results of one experiment can only be used to compare the risk of NH_3 emissions between the fertilizers and slurries, but the NH_3 emission measured using closed systems will largely underestimate the real emissions. The total emission of NH_3 and N_2O in the experimental period was calculated by linear interpolation of the fluxes determined at different times.

2.2. Pot Experiment

2.2.1. Set Up. A greenhouse pot experiment with ryegrass (*Lolium perenne* L., Barnhem) was designed as a simple two-factor treatment. The aim of the experiment was to quantify ANR, and NH_3, and N_2O emissions at different soil water contents (50, 60, and 80% of water holding capacity), as soil water contents may affect the N losses by NH_3 and N_2O emission and by that ANR of fertilizers. The experiment included an unfertilized control, two fertilizers (calcium ammonium nitrate applied as solid fertilizer and liquid ammonium nitrate), an untreated pig slurry, surface-applied MC, incorporated MC, incorporated mixture of MC and pig slurry, and an acidified MC. A mixture of pig slurry and MC was used as an N source because this is often used in practice. Application of MC required specific application techniques, but the application of mixtures of MC and slurries does not require specific application equipment. Incorporation and acidification of MC were tested as measures to abate NH_3 emission. The mixture of pig slurry and MC and the acidified MC were prepared three days before application to the pots. The MC was acidified by slow addition of 175 ml 2 M H_2SO_4 to 1 L MC in a beaker (0.7 $mol{\cdot}H{\cdot}L^{-1}$ MC). The pH of the acidified MC was 5.08 after 12 hours. All N treatments were carried out at three soil water contents and four replicates per treatment (in total 96 pots).

The tested pig slurry and MC were obtained from plant D but collected at a different time than the sample used in the incubation experiment. The experiment was conducted using 5.5-L plastic pots with a height of 22 cm and a diameter of 20 cm. The pots were filled with a loamy sand soil (3.0% organic matter and 4.1% clay) with only low amounts of available nitrogen (1 M KCl extract: <0.6 mg NH_4-N/kg dry matter and 7.3 mg NO_3-N kg dry matter) collected at the Droevendaal experimental farm (Wageningen 51°59′N, 5°39′E, The Netherlands). Each pot was filled with 6 kg of fresh soil. A watering tube with a diameter of 5 cm was placed in the middle of the pot to attain an even spread of moisture throughout the soil after watering. Seven weeks before the start of the experiment, grass was sown. To each pot, an additional amount of 0.8 kg of fresh soil was added together with 3 grams of grass seeds (*Lolium perenne* L., Barnhem: 3 g of seeds per pot). After six weeks, the grass sod developed in the pots was cut to a height of approximately 5 cm. In the week that followed, different soil water contents were established by daily giving different amounts of water resulting in 50%, 60%, and 80% of the water holding capacity. These water contents were maintained gravimetrically during the whole experiment. The water was added via the watering tube in each pot.

Incorporation of slurry into the soil by injection was simulated by creating a slit in the middle of the of the pot in the grass sod with a knife to a depth of approximately 5 cm.

Surface application of slurry was simulated by applying the slurry between the grass in the middle of the pot. The application rates of slurry and MC were based on results of analyses of the composition of these products just after collection of 1 to 2 weeks before experiments started. As the N content may change during storage and varies between batches, the N content of the actual batches used in the pot experiment was analysed after at the time of application. For some of the products, the N content was different that the N content which was used to derive the N application rates in the experiment. As the N content alters during storage and varies between batches, the N content of the actual batches used in the pot experiment was analysed after the start of the experiment, resulting in different N additions between the treatments. The N application rates were 10.5 g N m^{-2} for fertilizers and pig slurry, 6.6 g N m^{-2} for (acidified) MC, and 8.3 g·N·m^{-2} for the mixture of pig slurry and MC. During the experimental period, the temperature in the greenhouse generally varied between 18 at night and 20°C during day time. The treatments were applied after a warm period.

2.2.2. Measurements. Emissions of N_2O and NH_3 were measured using flux chambers (height 10 cm) connected with tubes to an Innova 1312 photoacoustic gas analyser. The tube to the gas analyser was heated to prevent water condensation in the tube. The NH_3 concentration in the headspace of the flux chamber was measured at 0 and 4 minutes after closing the flux chamber. NH_3 measurements were performed during the first three days after the N application. After this period, NH_3 emissions were negligible. Emission of N_2O was calculated from the change in concentration between 0 and 30 minutes after closing the flux chamber. The emissions were calculated using the volume of the flux chamber and tubing (4.26 L) and area of the soil surface (314 cm^2). The measured N_2O concentrations in the headspace were corrected for the amount of N_2O which was pumped from one flux chamber into the next flux chamber. This amount was calculated by multiplying the internal volume of the gas analyser and connecting tubes (about 2.5% of the headspace volume) with the N_2O concentration in the analyser and tubes (which is equal to the N_2O concentration of the previous measurement). Grass was cut at approximately 5 cm above the soil after 27 days and after regrowth, at 56 days. The dry matter content of the grass was determined after drying for 48 h at 70°C. Total N contents were determined spectrophotometrically by means of segment flow analysis [27].

2.2.3. Calculations and Data Analysis. The apparent nitrogen recovery (ANR) was calculated as the ratio of the N uptake in the shoot and the applied N, corrected for the average shoot N from the unfertilized control treatment at the same soil moisture content. The relative N fertilizer value (NFRV) of an organic fertilizer is the percentage of the applied N, which has the same effect on crop N yield as mineral fertilizer. The NFRV is calculated as the ANR of the tested product compared to the ANR of the CAN treatment at the highest soil moisture content.

2.3. Data Analysis. Data were statistically analysed using ANOVA with Genstat 16th Edition (VSN Int. Ltd.). For the incubation experiments, the between-treatment differences in log-transformed NH_3 and N_2O emissions were tested using Fisher's protected LSD analysis. The data were log-transformed to stabilize variance. For the pot experiment, a two-way ANOVA was performed for treatment and soil moisture content as factors and their interactions. A three-way ANOVA was performed for the N_2O and NH_3 emissions in the pot experiment including the factor time of analysis. Between-treatment differences were tested using Fisher's protected LSD analysis. Except the NH_3 emission, all tested parameters of the pot experiment did have a normal distribution. The NH_3 emissions were not normally distributed, also after log transformation, and were analysed using the one-way nonparametric Kruskal–Wallis test.

3. Results

3.1. Composition of the Products. Table 1 shows the composition of the tested products. The dry matter contents were lowest in the MC (on average 34 g·kg^{-1}), intermediate in the pig slurries (89 g·kg^{-1}), and highest in the solid fractions (284 g·kg^{-1}). The N contents in the fresh product were highest in the solid fraction and that of NH_4^+-N was highest in the MC. The P content of MC was on average 0.3 g·kg^{-1} and much lower than those of pig slurries (2.0 g·kg^{-1}) and solid fraction (7.0 g·kg^{-1}). The ratio of NH_4^+-N to total N was higher for MC (0.84) than slurries (0.62) and solid fraction (0.44). The average pH of MC was 8.0 and was higher than the average pH of pig slurries of 7.7.

3.2. NH_3 and N_2O Emissions from Arable Soil. Ammonia emission from MC, pig slurry, and the solid fraction surface applied to arable soils was highest directly after application and decreased within a week to levels similar to the control (Figure 1). The NH_3 emission from surface-applied urea followed a different pattern and peaked at day 2 (Figure 1). The emission from surface-applied CAN was negligible. Incorporation decreased NH_3 emission, and emission was negligible for most fertilizers and manures after incorporation (Table 2). Emission of NH_3 after surface application was on average statistically higher for MC, followed by pig slurry, and solid fraction (Table 2). This was not shown for plant B; NH_3 emission from untreated slurry B was significantly higher than that from MC B. The total NH_3 emission from surface-applied urea was similar to that from surface-applied MC A and B but lower than that from MC C and D.

Emission of N_2O from fertilizers and manures gradually increased after application to soil (Figure 2). Application of water at day 7 increased N_2O emissions of all treatments. Total emission N_2O was on average significantly higher after incorporation than after surface application (Table 2). For products of plants A, B, and C, the N_2O emission at incorporation in the arable soil was highest for MC, followed by untreated slurry and the solid fraction (Table 2). However, the differences were in most cases not statistically

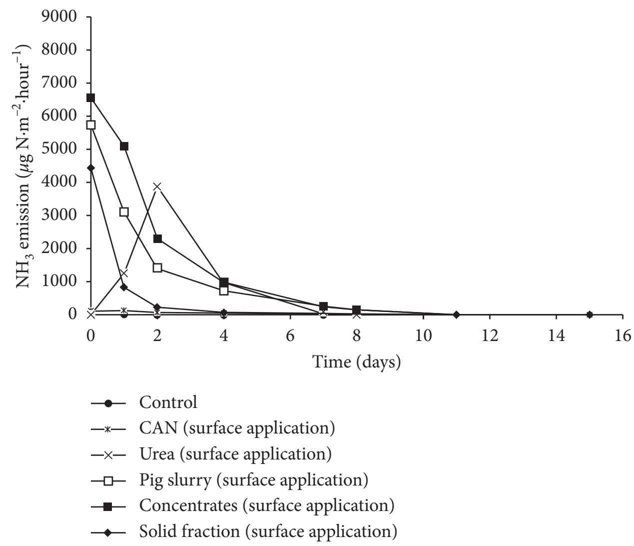

Figure 1: Ammonia emission from surface-applied manure products (average of four plants) and fertilizers applied to an arable sandy soil. After 7 days, 7 mm water was added to simulate rainfall. See Table 2 for the total emissions of all treatments of this experiment.

Table 2: Total ammonia and nitrous oxide emissions from different fertilizers and application techniques.

Fertilizer	Ammonia emission (mg N m^{-2})			Nitrous oxide emission (mg N m^{-2})			
	Surface applied		Incorporated	Surface applied		Incorporated	
Control	−1	aa	−1	0	ab	0	a
Calcium ammonium nitrate	12	ab	4	5	bc	30	bc
Urea	229	ghij	8	156	gh	248	gh
Urean	15	bc	2	76	fg	47	bcde
Slurry A	285	hijk	12	53	def	97	def
MC A	360	ijk	−1	18	cd	179	fgh
Solid fraction A	173	fghi	0	12	bc	15	ab
Slurry B	316	ijk	13	78	efg	124	efg
MC B	125	fg	0	11	bc	129	fg
Solid fraction B	84	ff	−4	0	a	86	def
Slurry C	284	hijk	9	31	cdef	82	def
MC C	493	k	6	27	cde	167	fg
Solid fraction C	45	de	6	8	bc	43	bcd
Slurry D	155	fgh	10	193	h	297	hi
MC D	470	jk	−2	63	ef	111	cdef
Solid fraction D	32	cd	−1	431	i	646	i
One-way ANOVA							
Fertilizer	$P < 0.001$		$P = 0.537$	$P < 0.001$		$P < 0.001$	
Two-way ANOVA							
Fertilizer	$P < 0.001$; l.s.d.[1] = 0.66			$P < 0.001$; l.s.d.[1] = 0.25			
Application method	$P < 0.001$; l.s.d.[1] = 0.23			$P < 0.001$; l.s.d.[1] = 0.09			
Fertilizer × method	$P < 0.001$; l.s.d.[1] = 0.93			$P < 0.001$; l.s.d.[1] = 0.36			

[1]l.s.d. of log-transformed values. Results of an incubation experiment with samples from an arable sand soil. The statistics and least significant difference (l.s.d.) values are based on log-transformed values. Different letters indicate statistical significant differences between fertilizers.

significant. By contrast, for plant D, the N_2O emission from incorporated MC was statistically significant smaller than that from untreated slurry and solid fraction.

3.3. Greenhouse Pot Experiment. The highest N uptake by grass was obtained at the highest soil moisture content (80% water holding capacity) and using CAN and liquid NH_4NO_3 as the N fertilizer (Table 3). The nitrogen use efficiency (ANR) varied from 30 to 55% (Table 3). ANR and NFRV were significantly higher at 80% than at 50% water holding capacity (Table 3). The lowest ANRs were obtained for incorporated pig slurry (30–39%) and surface-applied MC (33–38%), while the highest ANRs were obtained for liquid NH_4NO_3 (45–53%) and acidified MC (43–55%). At the highest moisture content, the NFRV of incorporated (93%) and acidified MC (106%) was significantly higher than that of surface-applied MC (72%; Table 3). Averaged over all moisture contents, there was no statistically significant difference between incorporated and acidified MC, liquid

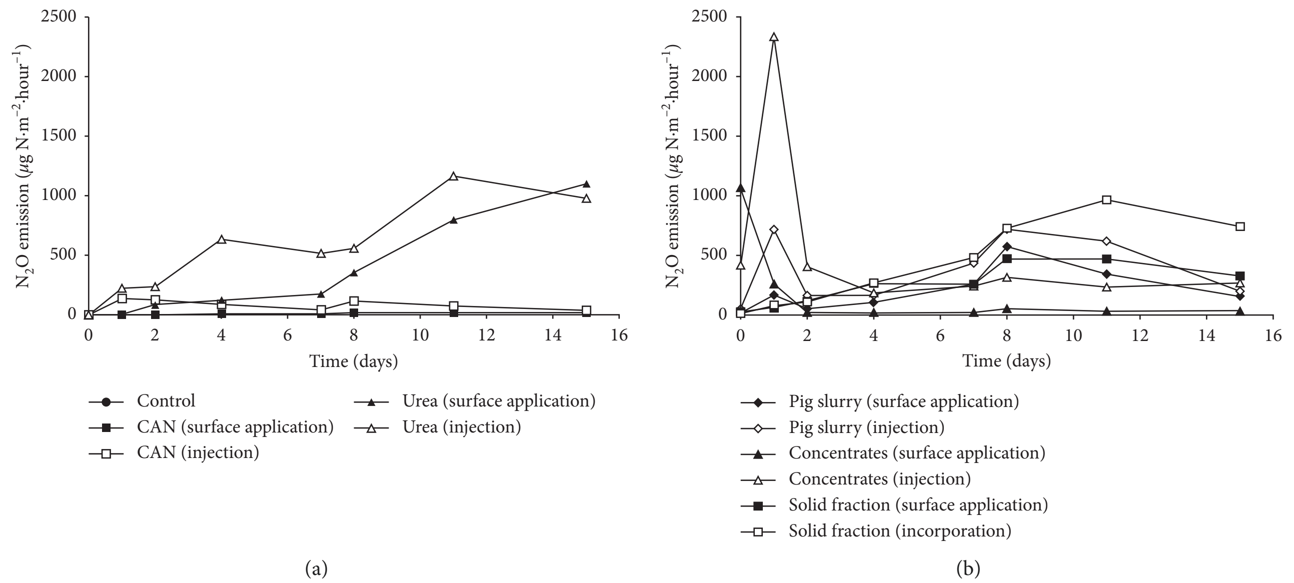

Figure 2: Nitrous oxide emission from incorporated and surface-applied fertilizers (a) and manures (average of four plants in (b)) applied to an arable sandy soil. Results of an incubation experiment with samples from an arable sand soil. After 7 days, 7 mm water was added to simulate rainfall. See Table 2 for the total emissions of all treatments of this experiment.

NH_4NO_3, and CAN (Table 3). The NFRV of the incorporated mixture of pig slurry and MC was 74–82% and between those of incorporated pig slurry (58–76%) and incorporated MC (83–106%).

Emission of NH_3 emission could only be detected at the day of the treatment, and emissions were negligible in the days thereafter (results not shown). The highest NH_3 emission was measured for surface application of MC at the lowest moisture content. No NH_3 emission could be determined for CAN, liquid NH_4NO_3, and acidified MC. The N_2O emissions in the pot experiment were significantly affected by the N source, the soil moisture content, and its interaction (Table 3). The highest N_2O emission was found for pig slurry and the mixture of pig slurry and MC (Table 3). The N_2O emission of acidified MC was lower than of incorporated MC.

4. Discussion

4.1. Emission of NH_3. It was hypothesized that the NH_3 emission from MC was smaller than that from untreated pig slurries because the N in MC infiltrates more rapidly into the soil than the N in slurries. However, the results of the incubation experiment showed that NH_3 emission at surface application was on average higher for MC than for untreated pig slurry, solid fraction, and mineral N fertilizer. Obviously, the positive effect on ammonia emission of the higher fraction of NH_4 in total N and the higher pH of MC than of untreated slurry was larger than the negative effect of the low dry matter content. In various studies, mechanical separation decreased NH_3 emissions after manure application, which was attributed to the lower dry matter content of the liquid fraction, by which the ammonium rapidly infiltrates into soil [18–21]. Application of the liquid fraction of pig slurry reduced NH_3 emission by an average of 25% compared with untreated pig slurry in a study of Chantigny et al. [20]. By contrast, in an experiment of [28], NH_3 emissions of the liquid fraction of raw slurry increased by about 60% compared to raw cattle slurry. This was probably due to its higher pH and fraction of ammonium in total N.

There were considerable differences in NH_3 emission between MC of the plants A, B, C, and D. These differences could not be explained by differences in composition (not shown), which is most likely due to the fact that were differences between the plants in composition of the treated slurry and in the method of separation and treatment of manure.

The incubation experiment (Table 2) and the pot experiment (Table 3) showed that incorporation of MC in the soil significantly reduced NH_3 emission. Incorporation of manure is considered a highly efficient technique to abate NH_3 emission [29]. The NH_3 emission after sod incorporation of MC to cereals was 3% of the applied NH_4-N in the MC and 12% when applied via a trailing hose dosing machine in a field study [30]. The NH_3 emission from MC applied with sod incorporation into grassland averaged 8% of the applied NH_4-N in this study. Decreasing the pH of slurry by acidification is another efficient option to reduce ammonia emission [31]. In the pot experiment, the NH_3 emission of the acidified MC was negligible, while the emission from surface-applied MC was highest. With a proper application technique or acidification, NH_3 emission from MC can be reduced strongly. Additional NH_3 abatement techniques may be applied to decrease NH_3 emission, including dilution with water and application during weather conditions with relatively low NH_3 emission, i.e., wet conditions and low wind speed [32]. Contrary to the expectations, soil moisture had no significant influence on the NH_3 emission in the pot experiment. On the

Table 3: N uptake of grass (sum 1st and 2nd cut), apparent N recovery (ANR), nitrogen fertilizer replacement value (NFRV)2, total N_2O emission during the pot experiment, and average NH_3 emissions at the first day, at 50, 60, and 80% of the soil water holding capacity (WHC).

Treatment	N uptake (m^{-2})				ANR (%)				NFRV (%)				N_2O (mg N m^{-2})				NH_3 (g N m^{-2} day^{-1})		
	50%	60%	80%		50%	60%	80%		50%	60%	80%		50%	60%	80%		50%	60%	80%
Control	0.4	0.3	0.5	a									2	5	6	ab	0	0	0
CAN, surface-applied	4.9	5.3	6.0	d	43	47	52	bc	82	90	100	bc	17	11	19	c	0	0	0
Liquid NH_4NO_3, surface-applied	5.1	5.4	6.1	d	45	48	53	c	87	93	101	c	−2	2	10	a	0	0	0
Pig slurry, incorporated	3.4	3.9	4.5	c	30	36	39	a	58	69	76	a	12	21	34	d	0.2	0.1	0.1
MC, surface-applied	2.6	3.1	3.0	b	33	41	38	a	64	79	72	a	3	11	6	ab	0.9	0.3	0.3
MC, incorporated	3.3	3.5	3.8	c	44	48	49	bc	84	93	93	bc	9	3	16	b	0.1	0.2	0.4
Mixture pig slurry and MC, incorporated	3.6	3.8	4.1	c	39	42	43	ab	74	80	82	ab	17	11	37	d	0.4	0.2	0.2
Acidified MC, surface-applied	3.3	3.5	4.2	c	43	48	55	c	83	93	106	c	−1	−3	10	a	0	0	0
ANOVA1	a	a	b		a	ab	b		a	ab	b		a	a	b				
N source		<0.001				<0.001				<0.001				<0.001				$\chi^2 < 0.001$	
Moisture		<0.001				0.012				0.012				<0.001				$\chi^2 = 0.407$	
N source ∗ moisture		0.948				0.998				0.998				0.002					

1Values within columns with different treatments and different subscripts differ significantly ($P < 0.05$) and values in this row with different soil moisture contents and with different letters differ significantly ($P < 0.05$). 2Values are calculated as the relative ANR compared to the ANR at CAN 80% WHC.

one hand, a lower soil moisture content might increase the infiltration of manures, but on the other hand, air-filled soil pores may promote gaseous emissions [33]. Possibly the variation in moisture conditions in the pot experiment was too small to detect effects.

4.2. Emission of N_2O. It was hypothesized that the difference in N_2O emission between MC and untreated pig slurry is difficult to predict because many factors (and interactions between factors) affect the production of N_2O during nitrification and denitrification in soil. In the incubation experiment, the N_2O emission from incorporated MC was on average higher than from incorporated untreated slurry although there were differences between the different plants (Table 2). The N_2O emission of MC of plant C was lower than that of untreated slurry C; this was found both in the incubation study and pot experiment (Tables 2 and 3). The N_2O emission from the solid fraction of plant C was also high. As also indicated for NH_3 emission, the difference between plants could not be explained by differences in composition (not shown). This is most likely due to the fact that there were differences between the plants in composition of the treated slurry and in the method of separation and treatment of manure. It is not clear which factor caused the high N_2O emission from the untreated slurry and solid fraction of plant D.

Bertora et al. [34] found that the N_2O emission of nontreated pig slurry (N_2O emission was 4.8% of applied N) was higher than that of the liquid fraction (2.6%) and solid fraction (1.8%) of separated pig slurry. Chantigny et al. [20] found no clear effects on pig slurry treatment on N_2O emission. Slurries contain organic C, including volatile fatty acids [35]. Volatile fatty acids are effective energy sources for denitrifiers [36]. When available C is applied to a NO_3-containing soil under wet conditions, denitrifying bacteria may use the C as energy source and the NO_3 can be transformed into gaseous N_2O and N_2. Despite the separation of liquid and solid fractions, MC also contains volatile fatty acids [37]. The presence of volatile fatty acids may have increased the N_2O emission from MC. The high N concentration in MC (about a factor 1.5–2 higher than in pig slurry) in combination with the high pH may have increased NH_3 concentration in the soil. This may have resulted in NH_3 toxification of nitrifier bacteria which in turn may increase N_2O emission [38, 39]. These effects are likely to be similar to those found in urine patches, in which N_2O emission is also relatively high [40].

Incorporation of slurries and MC are techniques to reduce NH_3 emission. However, incorporation of both MC, slurries, and mineral fertilizers increased N_2O emission in the incubation experiment. Also in other studies, it was shown that incorporation of manure increases N_2O emission [4]. The higher N_2O emission by incorporation than by surface application is most likely due to three factors: (i) the NH_3 emission with incorporation is lower by which mineral N content in soil is higher; (ii) the oxygen concentration is lower in the soil than on the top of the soil, increasing the chance on denitrification and N_2O production during nitrification, and (iii) in case of manure, the incorporation of organic C in the soil may increase biological oxygen consumption and, by that, the chance on denitrification and N_2O production during nitrification.

There was no statistical significant difference in N_2O emission between surface-applied MC and -acidified MC (Table 3). Also Fangueiro et al. [41] showed that acidification of slurry did not increase N_2O emission. Acidification instead of incorporation could be an option to decrease NH_3 emission with limited risk on increasing N_2O emission, but more tests are needed to confirm this because the fraction of N_2O in the total N loss by denitrification increases when the pH decreases [42].

Nitrification inhibitors can reduce the emission of N_2O from ammonium fertilizers with 30–50% [43, 44]. Adding nitrification inhibitors could be an option to decrease N_2O emission from MC. However, the effectiveness of nitrification inhibitors to decrease N_2O emission from MC has not been tested.

4.3. Nitrogen Use Efficiency. The efficiency of N in MC used as the fertilizer often depends on the NH_3 emission and the presence of organic N[14]. The NFRV of an organic fertilizer is the percentage of the applied N, which has the same effect on crop N yield as mineral fertilizer. In this study, the NFRV was determined by comparison with broadcast calcium ammonium nitrate (CAN), which is the most commonly used mineral N fertilizer in the Netherlands. The NFRV of incorporated MC in field experiments ranging from 54 to 84% [14, 16] were lower than in the pot experiment of this paper (93%) and 96% in the pot experiment of Klop et al. [17]. Probably, the difference in NFRV of MC between pot and field experiments is due to a lower NH_3 emission under the controlled conditions in the pot experiment. In the pot experiment (Table 3), the NFRV of MC was similar to that of liquid ammonium nitrate applied with the same incorporation technique. Similar results were found by Klop et al. [17]. The distribution of N in the soil differs between the broadcast applied CAN granules and of incorporated liquid fertilizers, and this could affect the N availability for crop roots and N transformation (mineralisation and denitrification) and be a factor that played a role in the differences in N use efficiency between CAN and the liquid fertilizers.

A long-term study demonstrated that higher grass yields can be achieved with separated liquid fraction of dairy slurry than with raw slurry at equivalent ammonium application rates [45]. This was attributed to more rapid soil infiltration of the liquid fraction, which reduces NH_3 emission. Removing solids from pig slurry by mechanical, chemical, and biological means reduced NH_3 losses from pig slurry applied to perennial grass [20]. MC should be incorporated or acidified to maximize ANR and to fulfil their potential as inorganic fertilizer replacement. Significant ANR differences between the four MC suggest the possibility for further optimization of the MC production process.

4.4. Use of Treated Manure. MC can be used as a liquid N-K fertilizer. The N in MC is mainly found in the NH_4 form (on average 84% of total N in the MC). The remaining N is organically bound. The pH of MC is high (about pH 8), so that MC should be incorporated to decrease NH_3 losses and increase ANR.

The solid fraction can be used in agriculture as a source of P and organic matter. The addition of iron flocculants to enhance separation of slurries in a liquid and solid fraction may reduce the short-time P efficiency of the solid fraction [46]. The solid fraction also contains N, from which 45% as NH_4-N (Table 1). This N should be considered in the fertilisation plan when farmers use solid fraction to decrease the risk of N leaching [47]. The NFRV of the solid fraction compared to CAN was 32 to 55% in field experiments with potatoes and 64% in an experiment with maize [48].

5. Conclusions

It is concluded that MC has a similar N fertilizer value as mineral N fertilizers if NH_3 emission is reduced by incorporation or acidification. Incorporation increased N_2O emission, and N_2O emission from incorporated MC was on average higher than from incorporated untreated pig slurry. Acidification instead of incorporation could be an option to decrease NH_3 emission with limited risk on increasing N_2O emission, but more tests are needed to confirm this. Adding nitrification inhibitors could be an option to decrease N_2O emission from MC, but the effectiveness of nitrification inhibitors to decrease N_2O emission from MC has not been tested.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

The authors would like to thank Popko Bolhuis, Eduard Hummelink, and Jaap Nelemans for their assistance in the greenhouse and laboratory. The study was supported by the Ministry of Agriculture, Nature and Food Quality in the Netherlands (Project BO-20-004-017), and Interreg IVB Project Biorefine.

References

[1] W. Steffen, K. Richardson, J. Rockström et al., "Planetary boundaries: guiding human development on a changing planet," *Science*, vol. 347, no. 6223, article 1259855, 2015.

[2] O. Oenema, A. Bleeker, A. Braathen et al., "Nitrogen in current European policies," in *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives*, M. A. Sutton, C. M. Howard, J. W. Erisman et al., Eds., pp. 62–81, Cambridge University Press, Cambridge, UK, 2011.

[3] G. L. Velthof, J. P. Lesschen, J. Webb et al., "The impact of the nitrates directive on nitrogen emissions from agriculture in the EU-27 during 2000–2008," *Science of the Total Environment*, vol. 468-469, pp. 1225–1233, 2014.

[4] Y. Hou, G. L. Velthof, and O. Oenema, "Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment," *Global Change Biology*, vol. 21, no. 3, pp. 1293–1312, 2015.

[5] L. Ma, F. Wang, W. Zhang et al., "Environmental assessment of management options for nutrient flows in the food chain in China," *Environmental Science and Technology*, vol. 47, no. 13, pp. 7260–7268, 2013.

[6] C. H. Burton, "The potential contribution of separation technologies to the management of livestock manure," *Livestock Science*, vol. 112, no. 3, pp. 208–216, 2007.

[7] L. Masse, D. I. Massé, and Y. Pellerin, "The use of membranes for the treatment of manure: a critical literature review," *Biosystems Engineering*, vol. 98, no. 4, pp. 371–380, 2007.

[8] A. Zarebska, D. Romero Nieto, K. V. Christensen, L. Fjerbæk Søtoft, and B. Norddahl, "Ammonium fertilizers production from manure: a critical review," *Critical Reviews in Environmental Science and Technology*, vol. 45, no. 14, pp. 1469–1521, 2015.

[9] J. G. Pieters, G. G. J. Neukermans, and M. B. A. Colanbeen, "Farm-scale membrane filtration of sow slurry," *Journal of Agricultural Engineering Research*, vol. 73, no. 4, pp. 403–409, 1999.

[10] L. Masse, G. Bellemare, and J. Dubreuil, "RO membrane filtration of pretreated swine manure with high levels of suspended solids," *Transactions of the ASABE*, vol. 55, no. 5, pp. 1815–1820, 2012.

[11] L. Thörneby, K. Persson, and G. Trägårdh, "Treatment of liquid effluents from dairy cattle and pigs using reverse osmosis," *Journal of Agricultural Engineering Research*, vol. 73, no. 2, pp. 159–170, 1999.

[12] P. Hoeksma and F. E. de Buisonjé, "Production of mineral concentrates from animal manure using reverse osmosis," in *Monitoring of Pilot Plants in 2012–2014*, Wageningen UR Livestock Research, Wageningen, Netherlands, 2015.

[13] J. J. Schröder, W. de Visser, F. B. T. Assinck, and G. L. Velthof, "Effects of short-term nitrogen supply from livestock manures and cover crops on silage maize production and nitrate leaching," *Soil Use and Management*, vol. 29, no. 2, pp. 151–160, 2013.

[14] J. J. Schröder, W. De Visser, F. B. T. Assinck, G. L. Velthof, W. Van Geel, and W. Van Dijk, "Nitrogen fertilizer replacement value of the liquid fraction of separated livestock slurries applied to potatoes and silage maize," *Communications in Soil Science and Plant Analysis*, vol. 45, no. 1, pp. 73–85, 2014.

[15] G. Holshof and J. C. van Middelkoop, *Stikstofwerking Van Mineralenconcentraten Op Grasland = N Fertilizer Replacement Value of Mineral Concentrates on Grassland*, Lelystad: Wageningen UR Livestock Research, Wageningen, Netherlands, 2014.

[16] J. C. van Middelkoop and G. Holshof, "Nitrogen fertilizer replacement value of concentrated liquid fraction of separated pig slurry applied to grassland," *Communications in Soil Science and Plant Analysis*, vol. 48, no. 10, pp. 1132–1144, 2017.

[17] G. Klop, G. L. Velthof, and J. W. Van Groenigen, "Application technique affects the potential of mineral concentrates from livestock manure to replace inorganic nitrogen fertilizer," *Soil Use and Management*, vol. 28, no. 4, pp. 468–477, 2012.

[18] P. Balsari, E. Dinuccio, E. Santoro, and F. Gioelli, "Ammonia emissions from rough cattle slurry and from derived solid and liquid fractions applied to alfalfa pasture," *Australian Journal of Experimental Agriculture*, vol. 48, no. 2, pp. 198–201, 2008.

[19] M. Hjorth, A. M. Nielsen, T. Nyord, M. N. Hansen, P. Nissen, and S. G. Sommer, "Nutrient value, odour emission and energy production of manure as influenced by anaerobic digestion and separation," *Agronomy for Sustainable Development*, vol. 29, no. 2, pp. 329–338, 2009.

[20] M. H. Chantigny, D. A. Angers, P. Rochette, G. Bélanger, D. Massé, and D. Côté, "Gaseous nitrogen emissions and forage nitrogen uptake on soils fertilized with raw and treated swine manure," *Journal of Environment Quality*, vol. 36, no. 6, pp. 1864–1872, 2007.

[21] B. Amon, V. Kryvoruchko, T. Amon, and S. Zechmeister-Boltenstern, "Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment," *Agriculture, Ecosystems and Environment*, vol. 112, no. 2-3, pp. 153–162, 2006.

[22] G. L. Velthof, P. J. Kuikman, and O. Oenema, "Nitrous oxide emission from soils amended with crop residues," *Nutrient Cycling in Agroecosystems*, vol. 62, no. 3, pp. 249–261, 2002.

[23] S. Qin, C. Hu, T. J. Clough, J. Luo, O. Oenema, and S. Zhou, "Irrigation of DOC-rich liquid promotes potential denitrification rate and decreases $N_2O/(N_2O+N_2)$ product ratio in a 0-2 m soil profile," *Soil Biology and Biochemistry*, vol. 106, pp. 1–8, 2017.

[24] D. Kool, E. Hoffland, E. Hummelink, and J. Vangroenigen, "Increased hippuric acid content of urine can reduce soil N_2O fluxes," *Soil Biology and Biochemistry*, vol. 38, no. 5, pp. 1021–1027, 2006.

[25] R. L. M. Schils, J. W. van Groenigen, G. L. Velthof, and P. J. Kuikman, "Nitrous oxide emissions from multiple combined applications of fertiliser and cattle slurry to grassland," *Plant and Soil*, vol. 310, no. 1-2, pp. 89–101, 2008.

[26] G. L. Velthof and O. Oenema, "Nitrous oxide fluxes from grassland in the Netherlands: I. Statistical analysis of flux-chamber measurements," *European Journal of Soil Science*, vol. 46, no. 4, pp. 533–540, 1995.

[27] I. Novozamsky, V. J. G. Houba, R. van Eck, and W. van Vark, "A novel digestion technique for multi-element plant analysis," *Communications in Soil Science and Plant Analysis*, vol. 14, no. 3, pp. 239–248, 1983.

[28] E. Dinuccio, W. Berg, and P. Balsari, "Effects of mechanical separation on GHG and ammonia emissions from cattle slurry under winter conditions," *Animal Feed Science and Technology*, vol. 166-167, pp. 532–538, 2011.

[29] S. Bittman, M. Dedina, C. Howard, O. Oenema, and M. Sutton, *Options for Ammonia Mitigation: Guidance from the Unece Task Force on Reactive Nitrogen*, NERC/Centre for Ecology & Hydrology, Edinburgh, UK, 2014.

[30] J. F. M. Huijsmans and J. M. G. Hol, *Ammonia Emission after Application of Mineral Concentrates on Arable Land and Grassland*, Plant Research International, Wageningen, Netherlands, 2011.

[31] S. Bittman, M. Dědina, C. Howard, O. Oenema, and M. Sutton, *Options for Ammonia Mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen*, Centre for Ecology and Hydrology, Bailrigg, UK, 2014.

[32] S. G. Sommer and N. J. Hutchings, "Ammonia emission from field applied manure and its reduction-invited paper," *European Journal of Agronomy*, vol. 15, no. 1, pp. 1–15, 2001.

[33] P. A. Roelle and V. P. Aneja, "Characterization of ammonia emissions from soils in the upper coastal plain, North Carolina," *Atmospheric Environment*, vol. 36, no. 6, pp. 1087–1097, 2002.

[34] C. Bertora, F. Alluvione, L. Zavattaro, J. W. van Groenigen, G. Velthof, and C. Grignani, "Pig slurry treatment modifies slurry composition, N_2O, and CO_2 emissions after soil incorporation," *Soil Biology and Biochemistry*, vol. 40, no. 8, pp. 1999–2006, 2008.

[35] H. Kirchmann and A. Lundvall, "Relationship between N immobilization and volatile fatty acids in soil after application of pig and cattle slurry," *Biology and Fertility of Soils*, vol. 15, no. 3, pp. 161–164, 1993.

[36] J. W. Paul and E. G. Beauchamp, "Relationship between volatile fatty acids, total ammonia, and pH in manure slurries," *Biological Wastes*, vol. 29, no. 4, pp. 313–318, 1989.

[37] P. Ehlert, J. Nelemans, and G. Velthof, *Stikstofwerking Van Mineralenconcentraten: Stikstofwerkingscoëfficiënten En Verliezen Door Denitrificatie En Stikstofimmobilisatie Bepaald*

Onder Gecontroleerde Omstandigheden. Nitrogen Replacement by Mineral Concentrates, Alterra Wageningen UR, Wageningen, Netherlands, 2012.
[38] P. Chalk and C. Smith, *Chemodenitrification. Gaseous Loss of Nitrogen from Plant-Soil Systems*, pp. 65–89, Springer, Berlin, Germany, 1983.
[39] J. Heil, H. Vereecken, and N. Brüggemann, "A review of chemical reactions of nitrification intermediates and their role in nitrogen cycling and nitrogen trace gas formation in soil," *European Journal of Soil Science*, vol. 67, no. 1, pp. 23–39, 2016.
[40] O. Oenema, G. L. Velthof, S. Yamulki, and S. C. Jarvis, "Nitrous oxide emissions from grazed grassland," *Soil Use and Management*, vol. 13, no. 4, pp. 288–295, 1997.
[41] D. Fangueiro, J. L. S. Pereira, S. Macedo, H. Trindade, E. Vasconcelos, and J. Coutinho, "Surface application of acidified cattle slurry compared to slurry injection: impact on NH_3, N_2O, CO_2 and CH_4 emissions and crop uptake," *Geoderma*, vol. 306, pp. 160–166, 2017.
[42] M. Shaaban, Y. Wu, M. S. Khalid et al., "Reduction in soil N_2O emissions by pH manipulation and enhanced nosZ gene transcription under different water regimes," *Environmental Pollution*, vol. 235, pp. 625–631, 2018.
[43] H. Akiyama, X. Yan, and K. Yagi, "Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: meta-analysis," *Global Change Biology*, vol. 16, no. 6, pp. 1837–1846, 2010.
[44] C. Gilsanz, D. Báez, T. H. Misselbrook, M. S. Dhanoa, and L. M. Cárdenas, "Development of emission factors and efficiency of two nitrification inhibitors, DCD and DMPP," *Agriculture, Ecosystems & Environment*, vol. 216, pp. 1–8, 2016.
[45] S. Bittman, D. E. Hunt, C. G. Kowalenko, M. Chantigny, K. Buckley, and F. Bounaix, "Removing solids improves response of grass to surface-banded dairy manure slurry: a multiyear study," *Journal of Environment Quality*, vol. 40, no. 2, pp. 393–401, 2011.
[46] J. J. Schröder, D. Uenk, and W. de Visser, *The Availability of Phosphate from Solid Fraction of Separated Liquid Manure*, Plant Research International, Wageningen, Netherlands, 2010.
[47] P. Sørensen and G. H. Rubæk, "Leaching of nitrate and phosphorus after autumn and spring application of separated solid animal manures to winter wheat," *Soil Use and Management*, vol. 28, no. 1, pp. 1–11, 2012.
[48] W. van Geel, W. van Dijk, and W. van den Berg, *Nitrogen Replacement Value of Mineral Concentrates in Potato: Report of Field Research in 2009 and 2010*, Praktijkonderzoek Plant & Omgeving, Lelystad, Netherlands, 2012.