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Increased nitrogen fertiliser value of cattle slurry by different slurry pre-treatments

K. Andersson · S. Delin

Abstract The nitrogen (N) fertiliser value of cattle slurry is often low, due to a high carbon/nitrogen (C/N) ratio limiting slurry N availability, and high viscosity leading to slow slurry infiltration and increased risk of ammonia emissions. In this study, the effect of treatments reducing the slurry C/N ratio in combination with measures to reduce ammonia emissions after slurry application was tested. Seven field fertilisation experiments were conducted in winter wheat fields and grass leys in southwest Sweden during a three-year period. Slurry types included were untreated cattle slurry (CS), the liquid fraction (LF) from screw-press separation of cattle slurry, and biogas digestate (BD) with cattle slurry as the main substrate. Application strategies included trailing hoses, trailing shoes, and acidified slurry applied with trailing hoses. Trailing shoe application was further studied in two additional experiments in spring oats. In winter wheat and grass ley, the N fertiliser value, expressed as Mineral Fertiliser Equivalents based on the amount of applied ammonium N (MFE_{NH4N}), was lowest for CS applied with trailing hoses (31%). Slurry separation and anaerobic digestion increased

MFE_{NH4N} to 55% and 52%, respectively. Slurry acidification increased MFE_{NH4N} for CS to 52% and for BD to 82%, while the effect for LF was non-significant. In most cases trailing shoe application did not increase MFE_{NH4N} compared with trailing hoses. In conclusion, this study shows that the N fertiliser value of cattle slurry can be increased in several ways, with a combination of anaerobic digestion and slurry acidification resulting in the largest increase.

Introduction

Livestock manure is a valuable source of N and other plant nutrients in crop production, but it is also a significant source of emissions of ammonia (NH_3) and greenhouse gases (Oenema et al. 2008). The fertiliser value of the manure is directly affected by N losses (ammonia, nitrate, and nitrous oxide) and by the availability of manure N in relation to the crop demands. The fertiliser effect of cattle slurry is usually less than e.g. pig slurry, due to its greater DM content, which implies a risk of high ammonia losses due to slow slurry infiltration, and high C/N ratio which leads to N immobilisation (Jensen 2013). The C/N ratio strongly influences the availability of manure N, with C/N ratios > 15 generally leading to

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a net immobilisation and C/N ratios < 15 giving a net mineralisation of N within 2–4 months after application (Webb et al., 2013). Studies have shown a negative linear correlation between C/N ratio and the short-term N fertiliser value of animal manure and other organic fertilisers (Sørensen and Fernández 2003, Sørensen et al., 2003, Delin et al., 2012). Comparing different organic fertilisers, Delin, Stenberg et al. (2012) found the highest N fertiliser values for biogas digestate and animal by-products, intermediate for cattle- and pig slurry and chicken manure, and lowest for solid manure and compost.

In Swedish crop production, almost 30,000 tons of plant-available N is applied as animal manure annually, of which 75% as cattle slurry (Statistics Sweden 2023). Band application with trailing hoses is used for 74% of the slurry, while 20% is broadcast spread and only 5% injected (Statistics Sweden 2023). The N fertiliser value of cattle slurry, expressed as Mineral Fertiliser Equivalents (MFE), is typically only 35–50% of applied total N (Jensen 2013), and hence, there is a potential for further improvement.

The C/N ratio of organic amendments influences their N availability (Delin, Stenberg et al. 2012), and hence treatments that reduce the slurry C/N ratio theoretically increase slurry N availability. One such process is anaerobic digestion, where a fraction of the slurry C is transformed to methane (CH_4) and carbon dioxide (CO_2) (Möller and Müller 2012). In Sweden, biogas production is an increasing sector, and currently 1.33 million tons of manure are anaerobically digested annually (Energigas Sverige 2023), corresponding to 6–7 percent of the total manure volume (Statistics Sweden 2023). Most of the manure is co-digested with other substrates such as food waste and waste products from the food industry and slaughterhouses (Energigas Sverige 2023). Every year, 2.5 million tons of manure-based biogas digestate are used as a fertiliser in Swedish crop production (Energigas Sverige 2023), compared with 21 million tons of undigested manure (Statistics Sweden 2023). Another process that reduces the slurry C/N ratio is mechanical solid–liquid separation, where C, organic N and phosphorus (P) are concentrated to the solid fraction. The majority of ammonium N remains in the liquid fraction (Møller et al. 2002), implying a smaller C/N ratio of the liquid fraction after separation. In Sweden, there is an increasing interest in using mechanical slurry separation for production of Recycled

Manure Solids (RMS), used as bedding material for dairy cows (Jeppsson et al. 2024).

Following land application, up to 50% of slurry N can be lost through ammonia volatilisation, with most of the losses occurring within the first 12 h (Oenema, et al. 2008, Hafner et al. 2018). Application techniques aimed at reducing ammonia emissions include band application with trailing hoses or trailing shoes and slurry injection in either shallow open soil slots or deeper closed soil slots (Misselbrook et al. 2002). Compared with broadcast spreading of slurry, the reduction in ammonia emissions from trailing shoe application, wherein the slurry is placed below the crop canopy, is generally larger than from trailing hoses, but there are also large variations within each application strategy (Webb et al. 2010. Pedersen et al. (2020a) reported an average reduction of 19% for trailing shoe application compared with trailing hoses, with the largest effect on a coarse textured sandy soil. In Swedish experiments on a silty clay soil, trailing shoe application reduced ammonia emissions from untreated cattle slurry by 27% compared with trailing hoses, while no reduction was observed for separated cattle slurry or biogas digestate (Andersson et al. 2023a). Misselbrook et al. (2002) reported a correlation between crop height and ammonia abatement for trailing shoe application in grass ley, and a smaller effect on arable land compared with grass. Slurry acidification has proven to be an effective measure to reduce ammonia emissions, with reductions by 75–97% reported for cattle slurry acidified with sulphuric acid to pH 5.5–6.0 (Seidel et al. 2017, Keskinen et al. 2022, Andersson et al. 2023a). For a wider range of pH values and acids, a review by Fangueiro et al. (2015) concluded that acidification of cattle slurry reduced ammonia emissions by 15–80%.

Identifying measures to increase the N fertiliser value of cattle slurry could have substantial positive effects, both from an environmental perspective and economically, by reducing the need for mineral fertiliser N input. Thus, the aim of this study was to conduct a thorough investigation of different strategies to improve the N fertiliser value of cattle slurry by slurry pre-treatments, in combination with technologies to mitigate ammonia emissions. There are no previous publications of these combinations of slurry pre-treatments and application techniques under Swedish growing conditions, with in general lower air temperature and greater soil clay content than in

many other European countries. The study consisted of field experiments with winter wheat and grass ley, on two different soil types. Trailing shoe application was further studied through field experiment in spring oats, to test whether the effect was greater in a spring sown crop, with more recently cultivated (and therefore less dense) soil than in autumn sown or perennial crops.

With untreated cattle slurry applied with trailing hoses as a reference, the hypotheses tested were that N fertiliser effect would be increased by 1) reducing C/N ratio, 2) applying slurry with trailing shoes, and 3) lowering slurry pH with the addition of sulphuric acid. It was also hypothesised that the largest effect would be achieved by combining a reduction of C/N ratio with either slurry incorporation by trailing shoes or by slurry acidification. From the combinations of slurry types, application strategies, and crops, and based on results from parallel experiments examining effects on ammonia emission from the same treatments (Andersson et al. 2023a), the following was expected: 4) a larger effect of trailing shoe application for untreated cattle slurry than for separated cattle slurry and biogas digestate, 5) a larger effect of trailing shoe application on less dense, newly cultivated soil, meaning more effect in spring oats than in winter wheat and grass ley, and 6) a larger effect of acidification for untreated slurry than for separated cattle slurry, due to its greater DM content and slower slurry infiltration.

Materials and methods

In total, nine field experiments were conducted in winter wheat, grass ley, and spring oats during 2019–2021. The experiments were two-factorial with the factors being slurry type and application strategy. The factor slurry type included the sub-factors 1) untreated cattle slurry (CS), 2) the liquid fraction from solid–liquid separation of cattle slurry (LF), and 3) biogas digestate mainly based on cattle slurry (BD). Sub-factors of the factor application strategy were 1) trailing hose application (TH), 2) trailing shoe application (TS), and 3) trailing hose application of acidified slurry (AC). The experiments in winter wheat and grass ley included all combinations of slurry types and application strategies (Table 1). The experiments in spring oats were smaller with only

one slurry type, BD, and two application strategies, TH and TS at two application rates. Additionally, all experiments had control treatments without slurry application, but with different mineral N fertiliser additions to keep track of crop N response (Table 1). Although the whole experiment received a small amount of mineral N fertiliser at growth start, the control treatment without any additional N is referred to as the unfertilised control treatment (N_0).

Soil, crop and weather conditions

All experiments were carried out at the Swedish University of Agricultural Sciences' two research stations Lanna and Götala, close to Skara in Southwest Sweden. At both sites, the soil type is classified as a Cambisol (FAO Soil Taxonomy). The soil at Lanna (58°20'N, 13°7'E) is a silty clay soil, with the clay content in the experiments being 41–45%, the sand fraction being 7–14%, and the rest silt. Organic matter content was 2.6–3.3% and pH (1:5 H_2O) 6.8–7.1. The crop rotation at Lanna is mainly cereal based, with hardly any addition of animal manure throughout the past 60 years. At Götala (58°22'N, 13°29'E), the soil is a sandy loam, comprised of 67–71% sand, 14–15% clay, and the rest silt. The organic matter content is 2.9–4.0% and pH (1:5 H_2O) 5.7–6.3. The crop rotation includes 3–4 years forage ley and annual crops, and frequent addition of animal manure. Amounts of easily available potassium (K), as determined by extraction with 0.1M ammonium lactate/0.4M acetic acid solution (AL extraction) at pH 3.75 (Swedish Institute for Standards 1993), is average at both sites in relation to Swedish fertilisation recommendations (Andersson et al. 2023a) (Table 2). The amounts of easily available phosphorus (P) extracted in the same way (P-AL), are somewhat low at Lanna and high at Götala (Table 2), due to the differences in long-term P addition with animal manure.

The climatic conditions were similar between the two sites. The air temperature during the growing season (April-August) was close to the 30-year average in 2019, while cooler than the average in 2020, and warmer than the average in 2021 (Fig S1). The precipitation during spring (May) was above average in 2019 and 2021 and below average in 2020. Total precipitation in May 2020 was slightly greater at Götala with 19 mm, compared with 8 mm at Lanna. Temperature and wind speed at slurry application

Table 1 Treatments and N application rates in the field experiments in winter wheat and grass ley, with three control treatments without slurry application and nine treatments with slurry application. The experiments were two-factorial, where the factor slurry type included untreated cattle slurry (CS), liq- uid fraction from solid–liquid separation of cattle slurry (LF), and biogas digestate mainly based on cattle slurry (BD). The factor application strategy included trailing hose application (TH), trailing shoe application (TS), and trailing hose applica- tion of acidified slurry (AC)

Mineral N Fertiliser type	Mineral N control treatment	N application rate in winter wheat (kg N ha^{-1})	N application rate in grass ley (kg N ha^{-1})
Ammonium nitrate	N_0—No nitrogen	0	0
Ammonium nitrate	N_{Normal}—Same as slurry treatments	70–75	60
Ammonium nitrate	N_{High}—Higher than slurry treatments	100–120	120
Slurry type	Slurry application strategy	N application rate in winter wheat (kg NH$_4$-N ha^{-1})	N application rate in grass ley (kg NH$_4$-N ha^{-1})
Untreated cattle slurry (CS)	Trailing hoses (TH)	70–75	60
	Trailing shoes (TS)	70–75	60
	Trailing hoses – acidified slurry (AC)	70–75	60
Separated cattle slurry (LF)	Trailing hoses (TH)	70–75	60
	Trailing shoes (TS)	70–75	60
	Trailing hoses – acidified slurry (AC)	70–75	60
Biogas digestate (BD)	Trailing hoses (TH)	70–75	60
	Trailing shoes (TS)	70–75	60
	Trailing hoses – acidified slurry (AC)	70–75	60

Table 2 Soil texture and nutrient status for each of the field experiments. Data from the latest soil inventory 2015–2017. Ww = winter wheat, Gr = grass ley, Oa = oats, L = Lanna, G = Götala, numbers represent the different years (2019–2021)

Exp	Clay	Sand	Silt	Org matter	pH (1:5 H$_2$O)	P_AL	K_AL	Mg_AL	P_HCl	K_HCl
	(%)	(%)	(%)	(%)		(mg 100 g^{-1} DW soil)				
Ww19L	41	10	49	3.1	6.8	3.3	12	20	49	270
Ww20G	15	67	18	3.5	6.3	11	14	11	130	160
Ww20L	42	12	46	3.3	7.0	3.4	10	33	45	250
Ww21L	45	7	48	2.7	7.1	3.3	13	36	42	320
Gr19G	14	69	17	4.0	6.5	34	29	13	190	220
Gr19L	43	14	43	2.6	7.0	4.4	16	21	37	300
Gr20G	14	71	15	3.1	5.7	18	13	4.5	180	180
Oa20G	14	69	17	2.9	5.9	18	12	6.4	150	180
Oa20L	41	10	49	2.7	6.9	3.8	12	23	41	280

varied widely (Table 3). Precipitation during the first days after slurry application was low in all the experiments, and in grass ley and oats in 2020 the soil was very dry, with a soil water content < 0.10 g g^{-1} dry weight soil (Table 3).

Nitrogen application rates and mineral N treatments

Target ammonium N application rate with slurry in the winter wheat experiments was 70 kg ha^{-1} in 2019–2020, and 75 kg ha^{-1} in 2021, while in all grass ley experiments 60 kg ha^{-1}. In spring oats, BD was applied at two target levels, 60 and 90 kg ammonium

Table 3 Soil and weather conditions on the day of slurry application and rainfall following slurry application, for all individual experiments. Ww = winter wheat, Gr = grass ley, Oa = spring oats. L = Lanna (silty clay), G = Götala (sandy loam). Numbers represent the different years (2019–2021)

Exp	Application date	Mean temp. day 1 (°C)[a]	Mean temp. day 1–3 (°C)	Mean wind (m s^{-1})[a]	Max wind (m s^{-1})[a]	Soil water content (g g^{-1} dry weight soil)	Rain within 7 days (mm)	Rain within 30 days (mm)
Ww19L	23 April	17.4	14.1	5.3	10.5	-	6.2	56.2
	24 April	16.7	15.0	5.9	14.7			
Ww20G	29 April	6.8	5.2	2.4	5.7	0.154	6.2	21.0
Ww20L	7 May	13.5	10.0	2.3	-	0.183	3	11.8
Ww21L	29 April	10.0	6.4	4.6	8.6	-	9.4	80.0
Gr19G	14 June	18.8	17.3	0.7	3.9	0.184	14.4	52.0
Gr19L	28 May	12.9	10.2	5.3	10.2	0.223	12.8	56.5
Gr20G	11 June	21.0	18.3	2.3	7.2	0.045	4.2	126.2
Oa20G	28 May	16.1	11.7	0.7	4.1	0.096	0	83.8
Oa20L	3 June	20.4	14.7	1.5	-	0.087	5.3	91.2

[a]Mean value for the time 10am to 10pm. Values indicated with " – " are missing

N ha^{-1}, for an evaluation of the trailing shoe performance at different application rates. The N application rates at slurry application were chosen to be somewhat below optimum for each crop, based on expected yield at the experimental sites and the N application rates recommended by the Swedish Board of Agriculture (Andersson, Frostgård et al. 2023b). This was done to avoid differences in slurry N availability to be hidden behind over-optimal N rates, in case of seasonal conditions constraining yields. To avoid N stress before slurry application, all experiments were fertilised with a moderate amount of mineral fertiliser N, in winter wheat generally 30 kg N ha^{-1} in early spring and in spring oats 20 kg N ha^{-1} at sowing (Table 4). The experiments were also fertilised with additional P, K, and sulphur (S) based on Swedish recommendations (Andersson et al. 2023a), in relation to crop need and soil status (Table 4). In experiment "Gr 2019 G" (Table 4), two of the four blocks were, in addition to the slurry application, accidentally fertilised with 60 kg ha^{-1} mineral fertiliser N. Since this fertilisation was equal over two entire blocks, N yield increase and MFE for the slurry treatments could still be calculated in the same way for all blocks, as there was still a N response.

Slurry treatment and application

The slurries used were: 1) untreated cattle slurry (CS) from a commercial organic dairy farm, 2) the liquid fraction (LF) from solid–liquid separation of cattle slurry from the same farm, and 3) biogas digestate (BD) from a biogas plant with a substrate mix containing 65% cattle slurry, 20% pig slurry, and the remaining 15% waste products from slaughterhouses and the food industry, along with a small fraction of chicken manure. Collection of CS was conducted from a pumping pit just outside the cow shed, and LF was collected from a larger storage tank, where the liquid fraction from a screw press separator (CRI-MAN SM 260/75 FA DM, CRI-MAN, Correggio, Italy) was continuously added during the winter. All slurries were collected in early April each year, and stored in 1000-L plastic tanks, in an unheated barn, until the start of the experiments.

For slurry acidification, the target pH was 6.0 for CS and LF, while 6.7 for BD. The higher target pH for BD was based on the experience from previous ammonia emission experiments (Andersson et al. 2023b), where the high buffering capacity of BD caused problems in reaching a pH of 6.0, and a pH 6.7 for BD resulted in similar ammonia abatement as pH 6.0 for the other slurry types. The amount of sulphuric acid needed for each slurry type was determined through titration of small slurry

Table 4 Nitrogen application rates with slurries, and amounts of macro nutrients added with mineral fertilisers for each experiment. Ww = winter wheat, Gr = grass ley, Oa = spring oats. L = Lanna (silty clay), G = Götala (sandy loam), numbers represent the different years (2019–2021). BD = biogas digestate, CS = untreated cattle slurry, LF = separated cattle slurry

Exp	Slurry application rate (tons ha^{-1})			Ammonium N (kg ha^{-1})			Total N (kg ha^{-1})			Macro nutrients with mineral fertiliser (kg ha^{-1})			
	BD	CS	LF	BD	CS	LF	BD	CS	LF	N	P	K	S
Ww 2019 L	20.6	41.2	41.2	71	69	71	104	152	132	30	15	0	19
Ww 2020 G	21.2	41.2	46.7	77	82	114	113	159	199	0	15	28	25
Ww 2020 L	21.2	41.2	46.7	77	91	91	112	167	205	74	0	0	11
Ww 2021 L	23.0	71.0	60.0	75	95	79	120	193	146	30	15	0	4
Gr 2019 G	17.6	35.3	35.3	54	61	65	80	113	116	0/60[a]	0	0	0
Gr 2019 L	17.6	35.3	35.3	56	63	66	122	141	135	50	14	14	25
Gr 2020 G	16.7	35.3	40.0	55	59	98	83	117	170	50	14	14	25
	BD low	BD high		BD low	BD high		BD low	BD high					
Oa 2020 G	16.7	25.0		54	80		82	123		0	0	0	0
Oa 2020 L	16.7	25.0		54	80		81	122		22	6	6	0

[a] 60 kg N ha^{-1} applies to only two of the blocks that were unintendedly fertilised

samples (150 ml). This was done for each batch of slurry, when they were delivered in spring. The slurry pH during titrations, and at field application was measured with a pH-meter (MW102, Milwaukee Instruments Kft., Szeged, Hungary). The amount of sulphuric acid added was similar for CS and LF, but considerably greater for BD (Table 5) despite a higher target pH, due to the high buffering capacity of BD. In 2019, slurry acidification was performed by injecting sulphuric acid diluted to 48% into the slurry spreader tank and mixing it with the slurry. However, that caused problems with excessive foaming. Therefore, in 2020 and 2021, sulphuric acid diluted to 48% was poured into half-filled 1000-L tanks with enough space for foaming a few hours before slurry application.

In all cereal experiments, the slurry was applied when the crop was at the late tillering stage, just before the start of stem elongation (DC 29–30), i.e. in late April or early May for winter wheat and in late May or early June for spring oats. In grass ley, slurries were applied after a first grass harvest, in early

Table 5 Slurry characteristics and amounts of sulphuric acid added to the different slurry types used in the fertilisation experiments

Experiments (n)	Biogas digestate (BD) 9		Untreated cattle slurry (CS) 7		Separated cattle slurry (LF) 7	
	mean	range	mean	range	mean	range
DM (%)	5.3	(4.8–5.9)	8.5	(7.3–9.8)	5.3	(4.6–6.1)
Tot N (kg ton^{-1})	5.0	(4.5–5.3)	3.5	(2.7–4.0)	3.7	(2.4–4.5)
NH$_4$-N (kg ton^{-1})	3.3	(3.1–3.7)	1.8	(1.3–2.2)	1.9	(1.3–2.4)
NH$_4$-N / Tot N	0.64	(0.46–0.69)	0.50	(0.44–0.54)	0.51	(0.44–0.57)
Tot C / Tot N	4.3	(3.7–4.8)	10.7	(9.8–12.4)	6.4	(5.4–8.1)
Tot C / Org N	12.8	(11.4–14.6)	21.4	(17.6–23.0)	13.2	(11.0–17.4)
pH	8.0	(7.6–8.4)	7.1	(6.8–7.7)	7.0	(6.9–7.2)
pH acidified	6.7	(6.2–7.1)	5.9	(5.3–6.4)	6.1	(5.8–6.4)
H$_2$SO$_4$ (96%) added (kg ton^{-1})	16.5	(14.7–19.3)	6.7	(5.5–9.2)	5.0	(3.7–7.2)

June. Slurries were applied with a tractor-mounted plot slurry spreader (Zunhammer GmbH, Traunreut, Germany), equipped with trailing hoses and trailing shoes at a distance of 0.25 m and a total working width of 3 m. Although the target ammonium N fertilisation rates were identical, the actual amounts of ammonium N added varied among experiments and slurry types, due to differences in N content between the slurry samples used as a basis for calculating the application rates and the slurry samples taken at field application (Table 4). This could have been caused either by non-representative samples sent for the preliminary analysis or by further mineralisation of organic N during the storage period of 1–2 months.

Slurry analyses

Samples of the slurries were taken from the slurry spreader at each application occasion. Ammonium N was determined by extraction with 2M KCl according to the modified Swedish standard ISO 11732 (International Organization for Standardization 2005) followed by an analysis with a flow injection analyser (FIAstar Analyzer (5000), FOSS, Hilleroed, Denmark). For total C and organic N, slurry samples were first dried in 100 °C and thereafter analysed according to modified standards ISO 10694 (International Organization for Standardization 1995) and ISO 13878 (International Organization for Standardization 1998), respectively, with combustion followed by elementary analysis (928 Series Macro Determinator (model CN928), LECO, St. Joseph, MI, USA). Total N was calculated as the sum of analysed organic N and ammonium N.

Yield

The harvested area for winter wheat and spring oats was 20 m^2 per experimental plot, and for grass ley 15 m^2. Cereal grain yield and fresh weight grass yield were recorded plot-wise. Grain samples were analysed for total N and for water content, and the grain yield was adjusted to 15% water content. From the analysed N content and the grain yield, the amount of N in harvested grain/grass (N-yield) was calculated. Grass samples were dried and analysed for DM and total N content, from which grass DM yield and N-yield were calculated.

Data treatment and statistical analyses

Nitrogen fertiliser value in slurry treatments was calculated as Mineral Fertiliser Equivalents (MFE), based on added total N for MFE_{totN} and on added ammonium N for MFE_{NH4N}. The MFE values were calculated separately for each block within an experiment, using Eq. 1. For each slurry treatment, the amount of mineral fertiliser N (F_M) that would result in the same N yield, was identified based on the N responses obtained from the different mineral N application rates (Fig. 1). The MFE value was then derived by dividing F_M with the amount of N added with manure (M), according to Jensen (2013).

$$MFE = F_M/M*100 \quad (1).$$

Statistical analyses were performed in Minitab, version 21.3.1 (Minitab18, Ltd., Coventry, UK). To verify assumptions for ANOVA, normal probability tests were performed. For winter wheat and grass ley, each of the experiments were first analysed separately, using the Mixed Effects Model in Minitab. Response variables were grain/grass yield, N-yield, MFE_{totN} and MFE_{NH4N}. Predictor variables were *slurry type* and *application strategy* (both fixed) and *block* (random). Interactions between the fixed factors were also included in the model. The least squares means from the experiment-wise analyses were then used in an analysis of all seven experiments combined. In this analysis, the factors included were *crop*, *slurry type,* and *application strategy* (all fixed), and *experiment* (random). Interactions among all fixed factors were also included in the model. Each of the two experiments in spring oats were analysed separately. The response variables were the same as for winter wheat and grass ley, and the predictor variables were *application strategy* and *N application rate* (both fixed), and *block* (random).

Results

Mineral N response

Nitrogen yield in the control treatment N_0, ranged from 24 to 79 kg N ha^{-1}. The nitrogen responses for mineral N application were linear for two of the winter wheat experiments and all grass ley experiments (Fig. 1), meaning N was limiting and this enabled the MFE of manure treatments to be easily
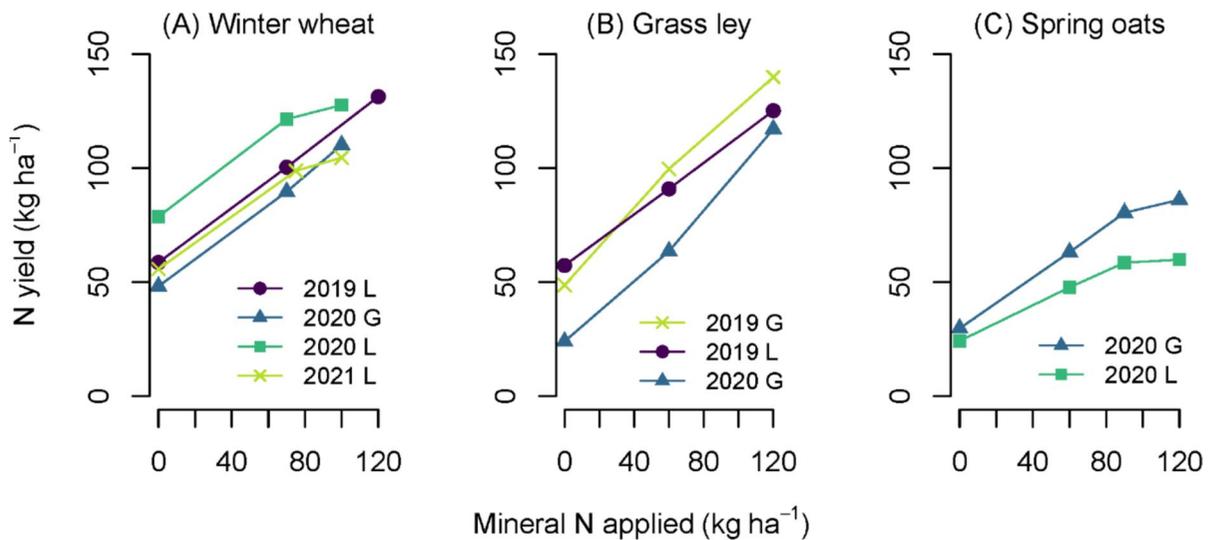
Fig. 1 Nitrogen responses for the mineral fertiliser treatments in each crop experiment for each year

calculated. For spring oats and for winter wheat at Lanna in 2020 and 2021, the N response levelled off with increasing N supply, which was considered when calculating MFE.

Cereal grain and dry matter grass yields

Winter wheat and grass ley

Yield in the unfertilised control treatment N_0 ranged from 3,500 to 5,300 kg ha^{-1} in winter wheat and from 1,700 to 4,800 kg DM ha^{-1} in grass ley (Table S1 and Table S2). Average yield increase in treatments with slurry application relative to unfertilised was 1,080 kg ha^{-1} in winter wheat and 1,250 kg DM ha^{-1} in grass ley. There were significant differences in yield among the slurry types (Table 6), but since the amount of N applied varied considerably (Table 4), comparing them directly is not relevant. Instead, the MFE values, where yield increases are placed in relation to N input, should be compared (Table 6). In both crops, slurry acidification increased yield and N yield by approximately 10% compared with non-acidified slurries, while trailing shoe application had no positive effect compared with trailing hoses.

Spring oats

In the spring oats experiments, grain yield in the control treatment was 1,700 – 2,200 kg ha^{-1} (Table S3) and due to a dry period after slurry application, grain yield was very low also in all slurry treatments, with less than 2,700 kg ha^{-1} at the clay soil and 3,000 – 3,900 kg ha^{-1} at the sandy loam soil. In the statistical analyses for spring oats, there was no interaction between the factors *N application rate* and *application strategy* for any of the response variables, therefore only the main effects are reported (Table 7). As expected, both grain yield and N-yield were higher at the higher N application rate at both experimental sites. At the clay soil site Lanna, trailing shoe application had no positive effect on any of the response variables, while at Götala grain yield and N-yield were increased by approximately 10% compared with trailing hoses.

Nitrogen fertiliser value

The MFE$_{NH4N}$ values (Table 6) indicate that the ammonium N in applied CS was on average around 40% as effective as mineral fertiliser N in both crops, compared with around 60% for LF and BD. For MFE$_{totN}$ but not for MFE$_{NH4N}$, there was a difference

Table 6 ANOVA main effects for the experimental factors slurry type and application strategy for winter wheat and grass ley separately. For the post-hoc test, values within each analysis sharing the same lowercase letter are not significantly different from each other at 0.05 level (Tukey's test). The main effect of the factor crop, and all interactions among fixed factors not included in this table were non-significant

	Winter wheat				Grass ley			
	Grain yield (kg ha^{-1})	N-yield (kg ha^{-1})	MFE$_{totN}$ (%)	MFE$_{NH4N}$ (%)	DM yield (kg ha^{-1})	N-yield (kg ha^{-1})	MFE$_{totN}$ (%)	MFE$_{NH4N}$ (%)
Slurry types								
p-value	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*0.036*	*0.002*	*< 0.001*	*0.001*
CS	5,464 a	77.5 a	18.0 a	36.6 a	4,268 a	62.6 a	21.3 a	42.2 a
LF	5,908 b	91.9 b	29.6 b	61.4 b	4,580 b	73.5 b	31.3 b	57.9 b
BD	5,961 b	86.9 b	40.4 c	60.3 b	4,549 ab	68.6 ab	39.5 c	65.1 b
Application strategies								
p-value	*0.008*	*0.008*	*< 0.001*	*0.001*	*0.008*	*0.003*	*< 0.001*	*< 0.001*
Trailing shoes	5,724 ab	83.9 ab	27.6 a	49.7 a	4,382 a	65.5 a	26.6 a	47.8 a
Trailing hoses	5,629 a	81.8 a	24.7 a	45.1 a	4,303 a	65.0 a	26.6 a	47.0 a
Acidified	5,979 b	90.5 b	35.7 b	63.6 b	4,713 b	74.1 b	38.8 b	70.4 b

Table 7 ANOVA results for grain yield, N-yield, and Mineral Fertiliser equivalents (MFE) in spring oats experiments. The main effect of the factor application rate, and all interactions among fixed factors not included in this table were non-significant. Within each column, values sharing the same lowercase letter are not significantly different from each other at 0.05 level (Tukey's test)

	Götala				Lanna			
	Grain yield (kg ha^{-1})	N-yield (kg ha^{-1})	MFE$_{totN}$ (%)	MFE$_{NH4N}$ (%)	Grain yield (kg ha^{-1})	N-yield (kg ha^{-1})	MFE$_{totN}$ (%)	MFE$_{NH4N}$ (%)
N application rates								
p-value	*< 0.001*	*< 0.001*	*0.979*	*0.979*	*0.020*	*0.034*	*0.486*	*0.486*
60	3,201 a	48.6 a	41.8 a	64.0 a	2,371 a	36.5 a	37.7 a	57.7 a
90	3,811 b	58.1 b	41.7 a	63.9 a	2,615 b	40.5 b	33.2 a	50.9 a
Application strategies								
p-value	*0.001*	*0.003*	*0.002*	*0.002*	*0.382*	*0.489*	*0.436*	*0.436*
Trailing hose	3,356 a	50.6 a	36.7 a	56.2 a	2,454 a	37.9 a	33.1 a	50.7 a
Trailing shoe	3,657 b	56.1 b	46.8 b	71.7 b	2,533 a	39.0 a	37.8 a	57.9 a

between LF and BD (Table 6), which reflects the lower application rate of total N in the treatment with BD, which had a higher relative ammonium N concentration (Table 5). Evaluating the different combinations of slurry types and application strategies, untreated cattle slurry applied with trailing hoses resulted in the lowest overall MFE$_{NH4N}$ while acidified biogas digestate gave the highest MFE$_{NH4N}$ (Fig. 2).

Crop availability of slurry N was evaluated by comparing MFE$_{totN}$ for acidified slurries, where the ammonia emissions are minimised. Slurry N availability as MFE$_{totN}$ was negatively correlated with slurry C/N ratio (Fig. 3). However, the correlation appeared mainly within each experiment (Fig. 3A) and not within each slurry type (Fig. 3B).

The four winter wheat experiments showed similar relationships in MFE values among treatments, but in two of them (Götala 2020 and Lanna 2020) the MFE values for all LF treatments were unexpectedly high (Fig. 4). In grass ley, the differences among treatments in individual experiments were non-significant in most cases, due to large experimental variation (Fig. 5).

The effect on MFE$_{NH4N}$ of trailing shoe application compared with trailing hoses was non-significant in
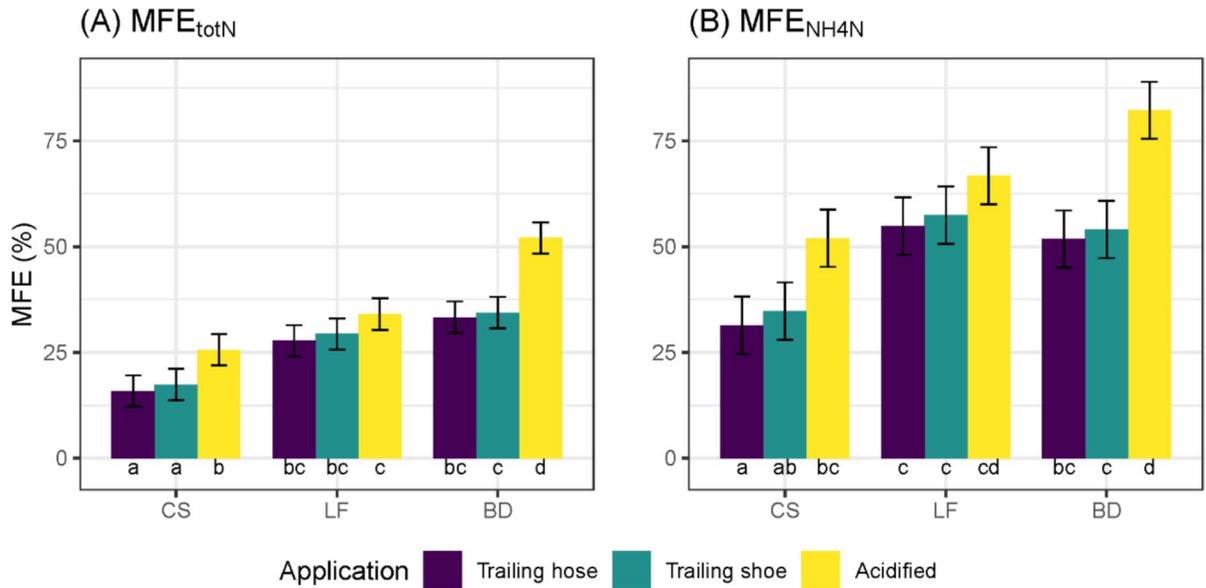
Fig. 2 Mineral Fertiliser Equivalents (MFE), mean values for all winter wheat and grass ley experiments (n=7), grouped by slurry type. Acidified slurries were applied with trailing hoses. Error bars represent standard error of the mean (SEM).

CS=untreated cattle slurry, LF=separated cattle slurry, BD=biogas digestate. Treatments in (A) and (B), respectively, sharing the same lowercase letter are not significantly different from each other at 0.05 level (Tukey's test)
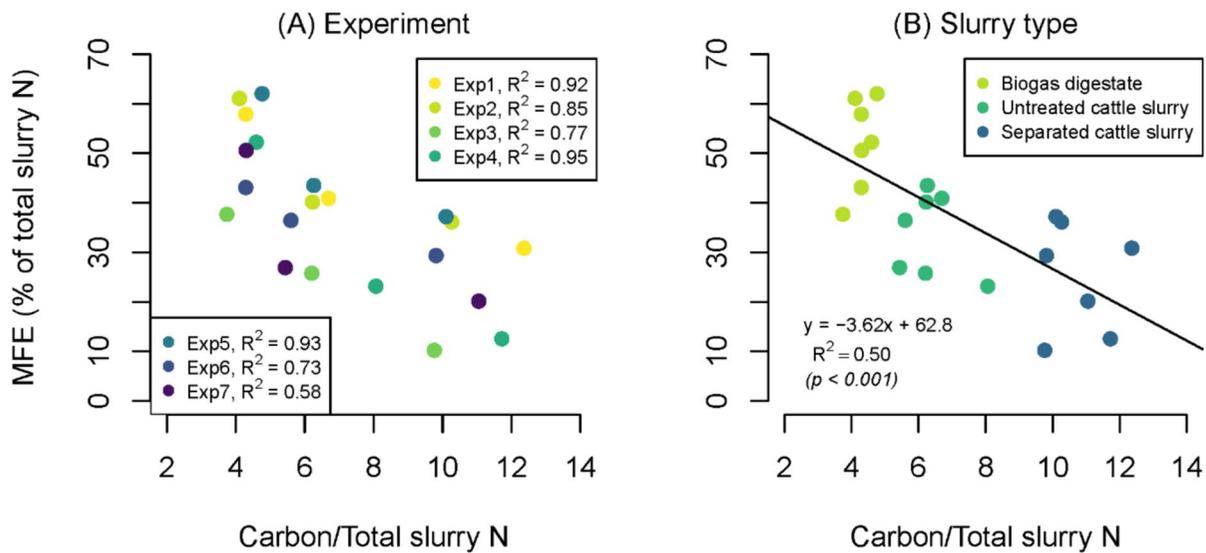
Fig. 3 Correlation between slurry fertiliser value as MFEtotN and slurry C/N ratio, analysed (A) for each individual experiment and (B) for all experiments together

all individual winter wheat and grass ley experiments and for all slurry types. For BD applied in spring oats, trailing shoe application increased the MFE values by 28% compared with trailing hoses at the sandy loam soil (Götala), while there was no difference at the clay soil (Lanna) (Table 7).

The effect of slurry acidification varied among slurry types, with the smallest increases in MFE

Winter wheat − individual experiments
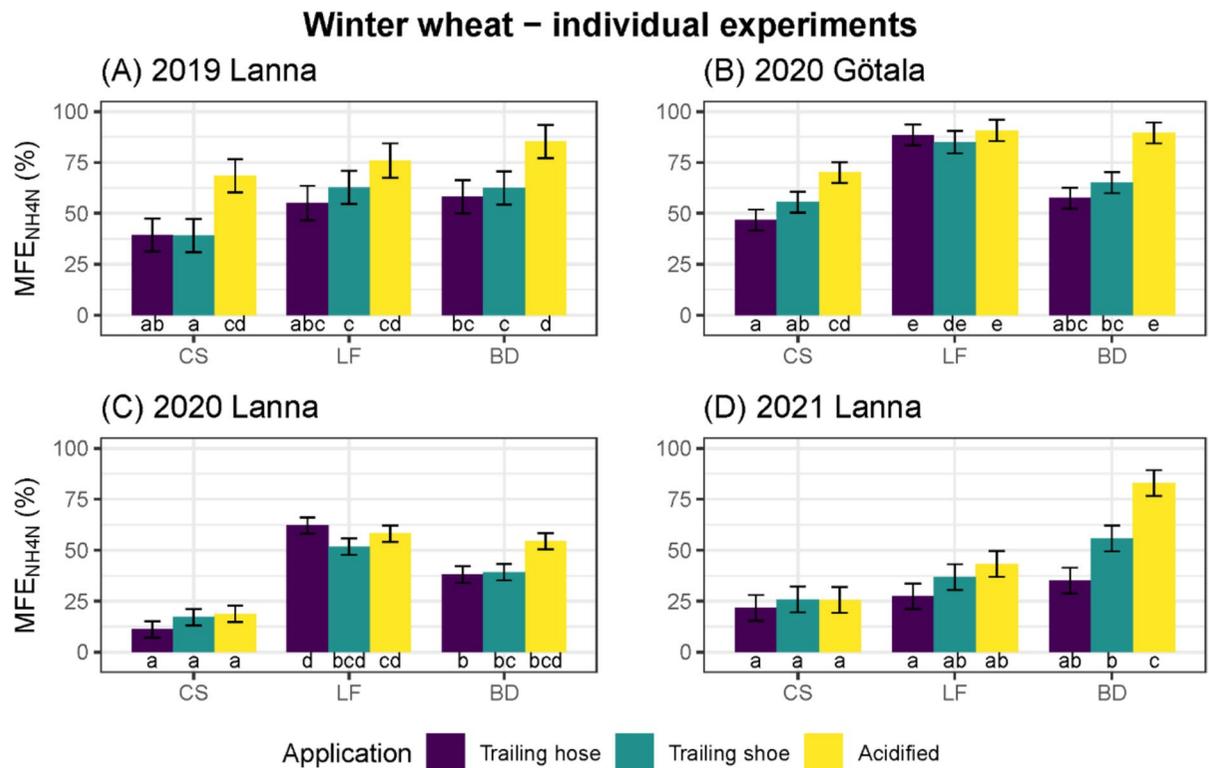
Figure. 4 Mineral Fertiliser Equivalents, MFENH4N, for all slurry treatments in each individual winter wheat experiment. Error bars represent standard error of the mean (SEM). Within each experiment, treatments sharing the same lowercase letter are not significantly different from each other at 0.05 level (Tukey's test)

values typically seen for LF and the largest for BD (Fig. 2). Further, in one of the winter wheat experiments, Lanna 2020, the effect of slurry acidification was non-significant for all slurry types. Biogas digestate had the highest original pH (8.0) and showed an overall good effect of acidification, despite problems in reaching the target pH 6.7 in some of the experiments. For CS, the effect of acidification on MFE was more varied, and related to the magnitude of pH reduction. In the two experiments with a significant acidification effect, pH was reduced by 1.2–1.7 units to 6.0 and 5.8, respectively, while in the other two, a pH reduction of 0.5–0.8 pH units to 6.4 after acidification gave non-significant effects. For LF, the effect of acidification was non-significant in all individual experiments.

Slurry pre-treatments increased MFE values

The results show that both solid–liquid separation and anaerobic digestion increase the MFE values compared with untreated cattle slurry. Biogas digestate had the highest overall MFE_{totN} (Table 6) as was expected, since BD had the highest proportion of ammonium N in relation to total N. Untreated and separated cattle slurry had similar fractions of ammonium N, and the lower MFE_{totN} value for CS than for LF is most likely related to its greater DM content and C/N ratio, as also shown in Fig. 3. A high DM content decreases slurry infiltration and thereby prolongs the time for ammonia losses after slurry application (Pedersen et al. 2021). A high C/N ratio leads to microbial N immobilisation, which reduces the N turnover rate in the soil and thus the availability of
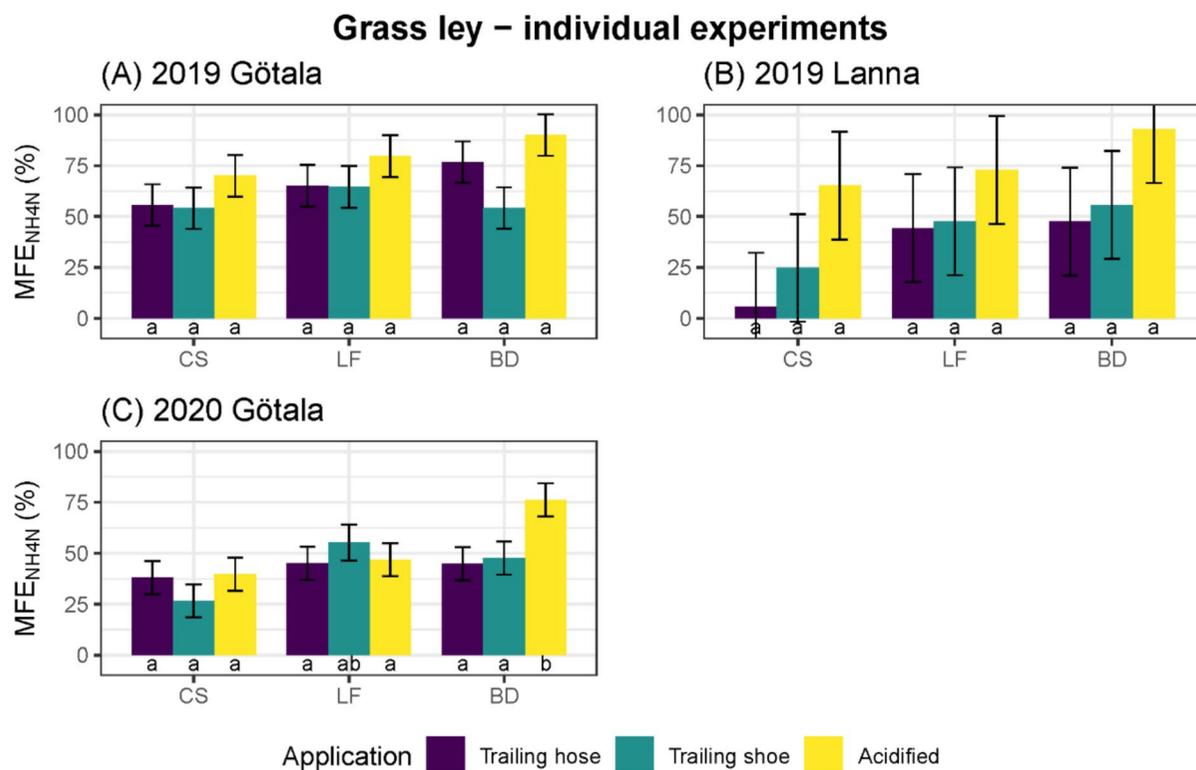
Figure. 5 Mineral Fertiliser Equivalents, MFENH4N, for all slurry treatments in each individual grass ley experiment. Error bars represent standard error of the mean (SEM). Within each experiment, treatments sharing the same lowercase letter are not significantly different from each other at 0.05 level (Tukey's test)

slurry N to the crop (Sørensen et al. 2003). The correlation between slurry C/N ratio and MFE$_{totN}$ was weaker in the current study compared with Sørensen et al. (2003), presumably because of larger variation in experimental conditions, including different crops, soil types, and years. This is also supported by the greater R^2 values for each individual experiment compared with all experiments analysed together. The lack of correlation within each slurry type (Fig. 3B) could be explained by the narrow range in C/N ratio for each slurry type in combination with the varying experimental conditions.

As in this study, an increased N fertiliser effect from slurry separation has also been reported e.g. by Pedersen et al. (2020b), and for anaerobic digestion by Frick et al. (2024), ten Huf, Reinsch et al. (2023), and Grillo et al. (2021). On the contrary, Tampere and Viiralt (2014) reported a slightly lower grass DM yield from fertilisation with digested cattle slurry, with an application rate based on ammonium

N content. The authors hypothesised that the lower grass yield was caused by a lower application rate for the digestate, with lower supply of other plant nutrients and organic matter.

It was hypothesised that BD would have the highest MFE$_{NH4N}$, based on its low C/N ratio. However, MFE$_{NH4N}$ was similar for LF (Fig. 2), which could be explained by higher ammonia emissions from BD, as measured in parallel experiments with the same treatments (Andersson et al. 2023b). The extra high MFE$_{NH4N}$ values for LF in both winter wheat experiments 2020 (Fig. 4b and c) could potentially also be due to a smaller C/N$_{org}$ ratio for LF in 2020 (11.1–11.2), compared with 2019 and 2021 (14.5 and 17.4, respectively), increasing the net N mineralisation after slurry application. This is in line with results from e.g. Pedersen, Christensen et al. (2020) and Chadwick et al. (2000)which showed a negative relationship between slurry C/N$_{org}$ ratio and N fertiliser value.

Varying effect of slurry acidification

The statistical analysis of all winter wheat and grass ley experiments together showed that slurry acidification increased crop yield, N yield, and slurry MFE (Table 6). However, there was a large variation among experiments and slurry types as seen in Fig. 4 and Fig. 5. For BD, the positive effect of slurry acidification on MFE in three of the winter wheat experiments (Fig. 4) suggests considerable ammonia losses from non-acidified digestate, irrespective of differences in temperature and wind speed during the first days after slurry application. In contrast, for LF, with non-significant effects of slurry acidification in all individual experiments (Fig. 4 and 5), the results suggest lower ammonia emissions from the non-acidified LF. This is also supported by results from ammonia emission measurements on the same slurry types as in the present study, showing the highest non-acidified emissions from BD and lowest from LF (Andersson et al. 2023a).

Although slurry acidification reduces the N losses, this is not always reflected in increased yield or N uptake in field experiments, because the variation in other factors such as soil and slurry characteristics and weather may have a greater influence on crop productivity (Webb et al. 2010). Varying effects of slurry acidification on crop response have been reported e.g. in a review paper by Fangueiro et al. (2015). Among more recent studies, despite reduced ammonia emissions, ten Huf et al. (2023) found no increase in yield or N-uptake in winter wheat from slurry acidification, while results in grass ley from Keskinen, Termonen et al. (2022) showed a positive effect in one year out of two. The results from the present study suggest that the largest agronomic effect of slurry acidification could be expected from slurries with high DM content or high pH.

No positive effect of trailing shoe application

No positive effect was seen from trailing shoe application in winter wheat and grass ley, since the performance of the trailing shoes was affected by a dry and compact soil surface, and the soil slots created were generally rather shallow and narrow. This resulted in the slurries being spread out beside the soil slots, which increased the slurry surface area and thereby the ammonia emissions. In Danish experiments, a combination of trailing shoes and rigid tines to break the surface crust worked well in reducing the slurry surface area (McCollough, Pedersen et al. 2022). However, no effect on crop yield was observed, and ammonia emissions were reduced only on a loose sandy soil. Crop properties are important, and short or sparse crops have been shown to give the poorest ammonia abatement effect from trailing shoe application (Misselbrook, Smith et al. 2002). This fits well with the conditions of the present study, where slurry application was completed shortly after the first harvest in grass ley, and before stem elongation in winter wheat. In ammonia emission experiments with the same slurry types and application strategies in grass ley on clay soil (Andersson et al. 2023b), trailing shoe application reduced the emissions significantly for CS, but not for BD and LF.

In older grass ley, such as that at Götala 2019, the grass tufts temporarily stopped the slurry flow from the trailing shoes, resulting in an uneven slurry application with slurry puddles. The increase in exposed surface area of the slurry likely increased the ammonia emissions, as previously shown by Pedersen, Andersson et al. (2021). In newly established ley with less distinct grass tufts and winter wheat, the phenomenon is less likely. However, depending on the pressure on the trailing shoes and their angle in relation to the soil surface, slurry application in situations with dry and hard soil could potentially provide the same result.

Despite a visually good performance of the trailing shoes in the spring oats experiment at Lanna, the effect on yield and slurry MFE of trailing shoe application was non-significant. This was most likely due to water stress, limiting crop N uptake and yield potential. This is also indicated by the low grain yield and N-yield (Table 7), since the more fertile clay soil at Lanna under optimal conditions has the highest yield potential of the two sites. The crop at Götala was less affected by the drought, and in line with our hypothesis, trailing shoe application increased the MFE values (Table 7). There was no difference in MFE between the two N application rates, most likely because of the relatively small slurry volumes. At both application rates (17 and 25 tons ha^{-1}) the soil slots created had a sufficient volume to contain the entire slurry volume applied, which is important to effectively reduce the

ammonia emissions (Hansen et al. 2003, Rodhe and Etana 2005).

Conclusions

Both mechanical slurry separation and anaerobic digestion increased the N fertiliser value of trailing hose applied cattle slurry, on average from an MFE_{NH4N} value of 30% to over 50%. For biogas digestate, the N fertiliser value was further increased by acidification, to an MFE_{NH4N} of 80%. The results were similar in winter wheat and grass ley, but larger experimental variation in the grass ley experiments resulted in mostly non-significant differences among slurry treatments. Averaged over all experiments, there was a negative relationship between MFE_{totN} and C/N ratio for the acidified slurries, indicating the potential fertiliser value under conditions with minimised ammonia losses. The increase in MFE from acidification for each slurry type reflects their vulnerability for ammonia losses, with the lowest being LF with a favourable combination of low DM content and low pH. For BD, the low DM content was counteracted by a high pH, increasing the ammonia emissions, and for CS, the high DM content prevented slurry infiltration, consequently prolonging the emissions. Regarding trailing shoe application, this study confirms the results from previous studies, showing that it is difficult to obtain an increased slurry N fertiliser value from trailing shoe application compared with trailing hoses, particularly on heavier soils and in short and sparse crops.

Data availability   The data are available from the authors on reasonable request.

Declarations

Conflict of interest   The authors declare no competing interests.

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