Vol.3, No.6, 799-805 (2012)
doi:10.4236/as.2012.36097

Agricultural Sciences

Relative effects of anaerobically-digested and conventional liquid swine manure, and N fertilizer on crop yield and greenhouse gas emissions

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Received 23 June 2012; revised 29 July 2012; accepted 8 August 2012

ABSTRACT

Anaerobic digestion is a promising technology that could provide an option for managing animal waste with reduced greenhouse gas emissions. A three-year (2006-2008) field experiment was conducted at Star City, Saskatchewan, Canada, to compare the effects of land-applied anaerobically digested swine manure (ADSM), conventionally treated swine manure (CTSM) and N fertilizer on grain yield of barley, applied N use efficiency (ANUE, kg·grain·kg^{-1} of applied N·ha^{-1}), ammonia (NH_3) volatilization and nitrous oxide (N_2O) emissions. Treatments included spring and autumn applications of CTSM and ADSM at a 1× rate (10,000 and 7150 L·ha^{-1}, respectively) applied every year, a 3x rate (30,000 and 21,450 L·ha^{-1}, respectively) applied once at the beginning of the experiment, plus a treatment receiving commercial fertilizer (UAN at 60 kg·N·ha^{-1}·yr^{-1}) and a zero-N control. There was a significant grain yield response of barley to applied N in all three years. The ANUE of ADSM or CTSM applied once at the 3× rate were lower than annual applications at the 1× rate (grain yield by 595 kg·ha^{-1} and NFUE by 6 kg·grain·kg^{-1} of applied N·ha^{-1}). On average, agronomic performance of ADSM was similar to CTSM. The APNU of N fertilizer was greater than the 3x rate but lower than the 1× rate of ADSM or CTSM. Ammonia loss from ADSM was similar to CTSM, except for much higher loss of NH_3-N from CTSM at the 3× rate applied in the autumn (8100 g·N·ha^{-1}) compared to the other treatments (1100 - 2600 g·N·ha^{-1}). The percentage of applied N lost as N_2O gas was generally higher for treatments receiving CTSM (4.0%) compared to ADSM (1.4%). In conclusion, the findings suggest that ADSM is equal or slightly better than CTSM in terms of agronomic performance, but has lower environmental impact.

Keywords: Ammonia Volatilization; Anaerobic Digestion; Barley Yield; Nitrogen Fertilizer Use Efficiency; Nitrous Oxide; Swine Manure

1. INTRODUCTION

In 2009, over 28 million hogs were marketed by Canadian farmers, with nearly one-half of that industry located in the prairie region. Approximately 90% of intensive livestock operations in the prairie region store manure in liquid form in a holding tank or lagoon [1] until it can be land-applied. Considerable amounts of methane (CH_4) are emitted to the atmosphere during storage [2] and, while land application of liquid swine manure provides an effective source of nutrients for crop production [3], high ammonia (NH_3) volatilization rates can occur following application [4-6]. In addition, soil-emitted nitrous oxide can also be stimulated [7]. Economically feasible, environmentally friendly, and socially acceptable management of animal wastes from intensive livestock operations is a key element for the future viability of this industry.

Anaerobic digestion of liquid swine manure is a promising technology that could provide a cost effective option for reducing greenhouse gas (GHG) emissions from liquid swine manure management by avoiding lagoon storage and the associated CH_4 emissions, and utilizing the biogas produced during digestion to displace fossil-fuels. Biogas digestion has the potential to directly or indirectly influence NH_3 volatilization and N_2O emissions. Anaerobic digestion decreases slurry viscosity and volatile fatty acid content, while increasing slurry pH and inorganic C content [8,9]. Reduced viscosity could decrease NH_3 volatilization from pig slurry [4,10], whereas increased pH and carbonate content could stimulate NH_3

volatilization [11,12]. Rubaek *et al.* [13] measured similar NH_3 volatilization following application of undigested and anaerobically digested pig slurry on grasslands in the United Kingdom. Similarly, Chantigny *et al.* [14] found no differences between undigested and anaerobically digested pig slurry from a site in Quebec, Canada. Conversely in another study also in Quebec, Chantigny *et al.* [7] measured lower NH_3 volatilization losses from digested compared to raw swine manure.

Land-applied liquid animal manures generally promotes soil-emitted nitrous oxide [7]. Anaerobic digestion of manures results in more recalcitrant products which may reduce the rate of microbial degradation and oxygen consumption in the soil [15-17], leading to less anoxic microsites which favor denitrifying activity. However, the inorganic nitrogen (N) content of digested manures tends to be higher, which could favour higher nitrification rates, and coincident N_2O production, and higher nitrate production—which would increase denitrification potential. The reported effects of manure treatments on nitrous oxide emissions are variable. Some authors reported similar N_2O emissions from raw compared to anaerobically digested manure [18], others have reported decreased emissions after anaerobic digestion [13,19,20]. Conversely, Chantigny *et al.* [7] reported increased emissions from digested compared to raw liquid swine manure, when the manures were injected into the soil.

Many factors, including environmental, soil, and application technique could potentially interact with manure type to influence NH_3 volatilization and N_2O emission following land-application of the material. To the authors' knowledge, there is very limited research information internationally [13] comparing the agronomic and environmental performance of land-applied raw versus anaerobically digested swine manure, and no published results for the Canadian prairie region. The objective of this study was to compare agronomic performance and gaseous N loss of land-applied anaerobically digested swine manure (ADSM) to conventionally treated (raw) swine manure (CTSM).

2. MATERIALS AND METHODS

A 3-year (2006-2008) field experiment was conducted at Star City (Typic Haplocryalf) Saskatchewan, Canada. Precipitation during the growing season (May, June, July and August) from 2006 to 2008, and long-term (30-year) average for the same period taken from the nearest Environment Canada Meteorological Station (AAFC Melfort), are presented in **Table 1**. Precipitation in the growing season was slightly below average in 2006, slightly above average in 2007 and much below average (especially in May during seeding) in 2008. Eleven treatments (**Table 2**) were arranged in a randomized complete block design with four replicates. Liquid manures were applied by the Prairie Agricultural Machinery Institute (PAMI) using a customized applicator which injects the material to a 10 cm depth. All plots were seeded to barley (*Hordeum vulgare* L.) in each of the three years (AC Rosser in 2006 and 2007; Newdale in 2008). Seeding dates and rates, weed control and harvesting operations followed standard agronomic practice.

Table 1. Monthly cumulative precipitation during 2006, 2007 and 2008 at Star City, Saskatchewan.

Year	Precipitation (mm)				
	May	June	July	August	Total
2006	63	73	39	46	221
2007	71	119	47	40	277
2008	6	32	117	22	177
30-year mean	46	66	76	57	245

Table 2. List of treatments and the corresponding total amount of N applied during a three-year field study at Star City, Saskatchewan.

Time of application	Product applied	Application rate	Total N applied (3-year cumulative)
Autumn	[a]ADSM-3x	21,450 $L \cdot ha^{-1}$	214
	ADSM-1x	7150 $L \cdot ha^{-1}$	205
	CTSM-3x	30,000 $L \cdot ha^{-1}$	403
	CTSM-1x	10,000 $L \cdot ha^{-1}$	360
Spring	ADSM-3x	21,450 $L \cdot ha^{-1}$	257
	ADSM-1x	7150 $L \cdot ha^{-1}$	255
	CTSM-3x	30,000 $L \cdot ha^{-1}$	343
	CTSM-1x	10,000 $L \cdot ha^{-1}$	326
	UAN	60 $kg \cdot N \cdot ha^{-1}$	180
	Control	0	0

[a]ADSM = Anaerobically digested swine manure, CTSM = Conventionally treated swine manure, UAN = Urea ammonium nitrate (liquid).

Conventionally treated swine manure was obtained from a commercial 1200 sow farrow-to-finish barn. Initial batches of the ADSM were obtained from a full-scale pilot mesophyllic digester situated by the commercial barn. Later batches (autumn 2007 and spring 2008) were obtained from a small-scale pilot mesophyllic digester operated by PAMI. Operating conditions for the small-scale digester were purposefully maintained to be comparable with the full scale version.

Previous research has indicated that application rates of CTSM, providing between 75 and 150 $kg \cdot N \cdot ha^{-1}$, are most effective for agronomic performance in this region

[21]. Based on analysis of the CTSM to be applied in the first autumn (2005) of the study, an application rate of 10,000 $L \cdot ha^{-1}$, a typical rate used by producers in Saskatchewan, would provide about 100 $kg \cdot N \cdot ha^{-1}$. Similarly, based on analysis of the ADSM supplied for application in the fall of 2005, an application rate of 7150 $L \cdot ha^{-1}$ provided a comparable amount of N. Treatments receiving CTSM and ADSM at 3× this rate were also applied. The "1×" rate was applied in each of the three years while the "3×" rate was applied only once at the beginning of the study. While not recommended, the latter treatment is a common practice employed by producers in this region. Rates were held constant on a volume basis throughout the study. However, the N concentration contained in both the CTSM and ADSM varied considerably from application period to application period. The cumulative N applied over the life of the study is presented in **Table 2**. To account for the differences in the actual N applied, grain yields and NH_3 and N_2O losses were normalized by expressing them as a ratio of N applied prior to statistical analysis. Applied N use efficiency (ANUE) of barley grain yield for the various treatments was calculated as: [(3-year total grain yield ha^{-1} for treatment) – (3-year total grain yield ha^{-1} for check)] ÷ (3-year total N applied to treatment).

Ammonia volatilization was measured using the "double-sponge open-chamber" technique [22], with measurements made on a set schedule for 2 - 3 weeks following application of the treatments. Briefly, a white polyvinyl chloride tube 20 cm long and 15 cm in diameter was inserted in the soil to a depth of 5 cm. A foam disk impregnated with an acid solution is inserted inside the chamber to absorb NH_3 evolved from the soil. A second disc closes the top of the chamber to allow for exchange of air between the chamber and the surroundings while scrubbing out atmospheric NH_3. The discs were prepared by washing twice with distilled water, twice with 0.001 M H_2SO_4 and twice with a glycerol-phosphoric acid solution. The lower disc was placed 5 cm above the soil surface, and the upper disc was placed 5 cm below the top of the cylinder. White plastic shields, supported at the corners by reinforcing bars, were placed 30 cm above the tops of the cylinders to protect the discs from rainfall but still allow air movement. Discs are exchanged at 1, 2, 4, 8 and 16 d after manure or fertilizer application, and rinsed in 0.5 M KCl. The concentration of ammonium in the extractant was determined with a Technicon Autoanalyzer [23]. Cumulative losses for each sampling period were calculated by interpolating between data points and integrating over time assuming a constant flux. Cumulative losses were normalized by subtracting the NH_3 lost from the check (no N applied) treatment and dividing that difference by the total N applied.

Nitrous oxide gas samples were collected using a non-flow through non-steady state chamber method [24]. Sample collection protocols were similar to those described by Rochette *et al.* [25]. Briefly, plexi-glass frames (22 cm × 45.5 cm and 10 cm high) were permanently installed in the soil between crop rows but covering manure or fertilizer injection bands, and lids were sealed to the frames for the collection period. Gas samples were drawn from the chamber headspace at three equally spaced time intervals, over a 60-minute period, by fully filling disposable 20-mL polypropylene syringes and transferring to pre-evacuated 13 mL exetainer™ glass tubes for transport to the laboratory. The concentration of N_2O in the sample containers was determined using a gas chromatograph equipped with a ^{63}Ni electron capture detector (ECD). The calculated minimum detectable difference for the system was <10 ppbv. Nitrous oxide flux rate was calculated as the first derivative of the second-order polynomial equation that best described the concentration versus time relationship, with adjustments for non-standard conditions of humidity, temperature and barometric pressure as described by Rochette and Hutchinson [26]. Time zero values were estimated using a method similar to that described by Anthony *et al.* [27]. A series of ambient air samples was collected at each sampling time. The mean of these samples was used as the time zero concentration. Gas sampling was done at least weekly, with increased frequency when expected emission activity was high (after snow melt and application of manure or fertilizer) and reduced frequency during the latter part of the season when soil-water contents were low. Seasonal estimates of N_2O emissions were calculated by interpolating between data points and integrating over time assuming a constant flux [28]. The percentage of applied N lost as N_2O-N was calculated by subtracting the N_2O-N lost from the check (no N applied) treatment and dividing that difference by the total N applied.

The data on various parameters were subjected to analysis of variance (ANOVA) using procedures as outlined in SAS [29]. Significant ($p \leq 0.05$) differences between treatments were determined using least significant difference ($LSD_{0.05}$).

3. RESULTS AND DISCUSSION

Rainfall was somewhat lower than the long-term mean during the July-August period in 2006 and 2007 (**Table 1**), but above average precipitation during the early part of the season (May-June) carried the crop through with good grain yields in 2006 (**Table 3**), and modest grain yields in 2007. Extremely low rainfall was received in May and June, above average rainfall in July, followed by very dry conditions through August of 2008. This somewhat erratic rainfall pattern resulted in modest grain

Table 3. Barley grain yields from various treatments for three years at Star City, Saskatchewan.

Time	N source/rate	2006	2007	2008	Mean
		kg·ha^{-1}			
Autumn	[a]ADSM-3x	6268	2213	3325	3935
	ADSM-1x	5609	2792	3497	3966
	CTSM-3x	5837	3256	3924	4339
	CTSM-1x	6375	4257	4699	5110
Spring	ADSM-3x	6250	2502	3258	4003
	ADSM-1x	6202	3050	4504	4585
	CTSM-3x	5946	2913	3653	4171
	CTSM-1x	6437	3228	4725	4797
	UAN	5387	2119	3725	3744
	Control	3487	1241	2629	2452
$LSD_{0.05}$		322***[b]	443***	305***	194***

[a]ADSM = Anaerobically digested swine manure, CTSM = Conventionally treated swine manure, UAN = Urea ammonium nitrate (liquid). [b]***Refers to significant at P < 0.001.

Table 4. Applied N use efficiency (ANUE) of barley grain yield for varying rates and sources of applied N at Star City, Saskatchewan.

Time	N source/rate	[b]ANUE kg·grain·kg^{-1} applied N·ha^{-1}
Autumn	[a]ADSM-3x	21bc
	ADSM-1x	22b
	CTSM-3x	14e
	CTSM-1x	22b
Spring	ADSM-3x	18d
	ADSM-1x	25a[c]
	CTSM-3x	15e
	CTSM-1x	22b
Spring	UAN	19cd

[a]ADSM = Anaerobically digested swine manure, CTSM = Conventionally treated swine manure, UAN = Urea ammonium nitrate (liquid); [b][(3-yr total grain yield ha^{-1} for treatment) – (3-year total grain yield ha^{-1} for control)] ÷ (3-year total N applied ha^{-1} to treatment); [c]The values are significantly different, when not followed by the same letter, based on $LSD_{0.05}$.

Table 5. Estimated ammonia-N (NH3-N) loss over three sampling periods from various treatments at Star City, Saskatchewan.

Time	N source/rate	Net NH_3-N loss g·N·ha^{-1}	[b]NH_3-N loss response g NH_3-N·kg^{-1} applied N·ha^{-1}
Autumn	[a]ADSM-3x	2600b	13ab[c]
	ADSM-1x	1200b	6b
	CTSM-3x	8100a	24a
	CTSM-1x	3000b	10b
Spring	ADSM-3x	1100b	5b
	ADSM-1x	1700b	8b
	CTSM-3x	1700b	6b
	CTSM-1x	2500b	10ab
	UAN	800b	6b

[a]ADSM = Anaerobically digested swine manure, CTSM = Conventionally treated swine manure, UAN = Urea ammonium nitrate (liquid); [b][(Cumulative NH_3-N lost from treatment) – (Cumulative NH_3-N lost from control)] ÷ [Cumulative NH_4-N applied]; [c]The values are significantly different, when not followed by the same letter, based on $LSD_{0.05}$.

yields. Compared to the zero-N control, there was a significant increase in grain yield of barley from application of ADSM, CTSM and N fertilizer in all three years. Similarly, other researchers have also found swine manure very effective in increasing crop yields in the years of application [3,21]. In general, the 1× application rates of ADSM or CTSM had the highest ANUE, the 3× application rates the lowest, and UAN was intermediate (**Table 4**). Further, ADSM tended to have similar or slightly better ANUE compared to CTSM.

Ammonia volatilization losses were generally quite low. Cumulative losses over all sampling periods ranged from less than a kilogram to about 3 kg of N·ha^{-1} (**Table 5**). The exception was the autumn applied CTSM-3x treatment which lost over 8 kg·N·ha^{-1}. When these losses were compared on a relative basis, (g NH_3-N·kg^{-1} applied NH_4-N), the autumn applied CTSM-3x treatment was significantly higher than all other treatments. In contrast, Rubaek *et al.* [13] did not find any difference in NH_3 volatilization loss from undigested versus anaerobically digested pig slurry on grassland in UK. This discrepancy between the two studies could be due to the differences in soil-climatic conditions and crop type.

Nitrous oxide emissions responded to the treatments in a relatively consistent fashion. Emissions were highest from the CTSM treatments, with particularly high losses in the first year of the study on the treatment receiving CTSM at the 3× rate (**Table 6**). When emissions were expressed as a percentage of applied N lost as N_2O, losses were significantly higher from the treatments receiving CTSM at the 1× and 3× rate compared to treatments receiving ADSM at the 1× rate and the UAN treatment (**Table 7**). The treatment receiving ADSM at the 3× rate was intermediate and significantly different from CTSM at the 3× rate applied in the autumn. Lower N_2O emissions from digested compared to raw swine manure was also reported by Chantigny *et al.* [7] and

Table 6. Estimated annual and three-year cumulative N_2O-N loss from various treatments at Star City, Saskatchewan.

Time	N source/rate	2006	2007	2008	3-year total
		kg·N·ha^{-1}			
Autumn	[a]ADSM-3x	2.9b	1.1b	3.4ab	7.4b
	ADSM-1x	1.3b	2.2b	2.0b	5.5b
	CTSM-3x	16.3a	1.8b	3.4ab	21.5a
	CTSM-1x	3.6b	5.9a	7.3a	16.8a
Spring	ADSM-1x	1.7b	2.1	2.2b	6.0b
	CTSM-1x	3.2b	5.4a	6.7a	15.3a
	UAN	1.1b	1.1b	2.3b	4.5b
	Control	0.8b	0.8b	1.6b	3.2b

[a]ADSM = Anaerobically digested swine manure, CTSM = Conventionally treated swine manure, UAN = Urea ammonium nitrate (liquid); [c]The values in each column separately are significantly different, when not followed by the same letter, based on $LSD_{0.05}$.

Table 7. Percentage of applied N lost as N_2O-N over three years at Star City, Saskatchewan.

Time	N source/rate	N_2O-N loss as a percentage of applied N
		%
Autumn	ADSM-3x	2.0bc
	ADSM-1x	1.1c
	[a]CTSM-3x	4.5a
	CTSM-1x	3.8ab
Spring	ADSM-1x	1.1c
	CTSM-1x	3.7ab
	UAN	0.7c

[a]ADSM = Anaerobically digested swine manure, CTSM = Conventionally treated swine manure, UAN = Urea ammonium nitrate (liquid); [c]The values are significantly different, when not followed by the same letter, based on $LSD_{0.05}$.

Vallejo *et al.* [20], and similar results have been reported for digested cattle manure [13,19,30]. Nyberg *et al.* [31] reported that some compounds present in anaerobically digested manure may have a depressive effect on soil ammonia oxidizers, thereby reducing the supply of substrate for N_2O production through nitrification and denitrification. Vallejo *et al.* [20] argued that because most easily degradable C present in manure is decomposed during anaerobic digestion, the C remaining in the digested manure is more stable and, therefore, less likely to stimulate denitrification and N_2O production as compared with the undigested manure.

4. CONCLUSION

There was a significant grain yield response of barley to applied N in all three years. The ANUE of barley for single applications of ADSM or CTSM at the 3× rate was lower than three annual applications at the 1× rate, while UAN was intermediate. The ANUE of ADSM and CTSM applied in autumn was equal to spring when applied at 1× rate and, in general, agronomic performance of ADSM was similar or better than CTSM. The APNU of N fertilizer was greater than the 3× rate but lower than the 1× rate of ADSM or CTSM. Ammonia losses for all treatments were low (<1 kg·N·yr^{-1}) except for CTSM at the 3× rate applied in the autumn (>8 1 kg·N·yr^{-1}). In general, NH_3 loss from ADSM was similar to CTSM, except for CTSM at the 3× rate applied in the autumn. The percentage of applied N lost as N_2O was generally higher for treatments receiving CTSM compared to ADSM or UAN, while N_2O losses from ADSM and UAN were similar. In summary, the findings suggest that ADSM is equal or better than CTSM in terms of agronomic performance, and has a lower environmental impact with regard to gaseous N loss.

5. ACKNOWLEDGEMENTS

We are grateful for the funding provided by the Environmental Technologies Assessment for Agriculture (ETAA) program, the excellent collaboration from the Prairie Agricultural Machinery Institute (PAMI), for access to raw and digested material provided by Cudworth Pork Investors Group Ltd. and Clear-Green Environmental Inc.

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