Nitrogen transformations and greenhouse gas emissions during composting of manure from cattle fed diets containing corn dried distillers grains with solubles and condensed tannins

Xiying Hao*, Mônica B. Benke, Chunli Li, Francis J. Larney, Karen A. Beauchemin, Tim A. McAllister

Agriculture and Agri-Food Canada, Lethbridge Research Centre, 5403 1st Ave S., Lethbridge, Alberta, Canada T1J 4B1

ARTICLE INFO

ABSTRACT

Condensed tannins (CT) in ruminant diets reduce ruminal N degradation, but there is little research on how these phenolic compounds alter N metabolism during manure composting. This study investigated effects of CT additives in cattle diets on N content and greenhouse gas (GHG) emissions from manure composting. This open windrow composting experiment consisted of two replications and three treatments being: (1) CK: manure from cattle fed a diet containing 860 g/kg barley (*Hordeum vulgare* L.) grain, 90 g/kg barley silage and 50 g/kg supplement on a dry matter (DM) basis, (2) DDGS: diet similar to (1) with 400 g/kg corn (*Zea mays* L.) dried distillers grain with solubles (DDGS) replacing barley grain, and (3) DDGS + CT: diet as described in (2) but with the addition of 25 g/kg DM *Acacia mearnsii* CT. After 56 days of composting (Phase 1), windrows in each treatment were thoroughly mixed and divided into four portions. Two portions received additional mature compost (100 kg/tonne DM) as a source of nitrite-oxidizing bacteria (NOB) and the other two received none. Portions were moved into individual bins for 57 days (Phase 2) of composting, followed by 104 days (Phase 3) of composting. Adding NOB had no effect on final compost properties or GHG emissions. Total C, total N and NH_4^+ in final compost were higher (P<0.001) in DDGS + CT than in the DDGS and CK treatments, increasing the value of the compost as a fertilizer. Including CT in the diet did not affect CO_2, CH_4 or N_2O emissions during composting. Results demonstrate that substituting DDGS for barley at 400 g/kg and adding 25 g/kg CT to cattle diets increases the agronomic value of the manure and compost as fertilizer without increasing GHG emissions.

This paper is part of the special issue entitled: Greenhouse Gases in Animal Agriculture – Finding a Balance between Food and Emissions, Guest Edited by T.A. McAllister, Section Guest Editors: K.A. Beauchemin, X. Hao, S. McGinn and Editor for Animal Feed Science and Technology, P.H. Robinson.

1. Introduction

Agricultural activities contribute 52% of CH_4 and 84% of N_2O anthropogenic emissions worldwide (EPA, 2006). Most of these emissions are from enteric fermentation and cultivated soils. However, contributions from livestock manure management are also important and are projected to increase in the next decade (EPA, 2006). Emissions of CH_4 and N_2O are an environmental concern because their global warming potentials are 25 and 298 (both based on a 100 year projection) times that of CO_2, respectively (IPCC, 2007). Another concern associated with manure production, storage and composting is NH_3 emissions. Atmospheric NH_3 deposition near feedlots has been linked to forest decline, reduced plant diversity in natural ecosystems and soil acidification (Aneja et al., 2001; Krupa, 2003; Hao et al., 2009a).

Motor fuel ethanol production generates a large amount of dried distiller's grains with solubles (DDGS), which have a high nutritional value for livestock (RFA, 2008). DDGS are increasingly used in beef cattle diets in North America, but their high N content leads to increases in manure NH_4^+ and pH (Leytem et al., 2008; Hao et al., 2009b), which could increase both NH_3 volatilization and N_2O emissions during manure storage and composting (Hao et al., 2009b, 2011).

Tannin containing compounds have been proposed as a dietary supplement for ruminants to reduce enteric CH_4 emissions (Animut et al., 2008; Patra and Saxena, 2009), NH_4^+ content in manure and NH_3 emissions from fresh manure (Śliwiński et al., 2002, 2004; Carulla et al., 2005). Tannins are polyphenolic compounds that inhibit microbial activity and form complexes with protein and cellulose (Makkar, 1993; Makkar et al., 1995a), reducing ruminal CH_4 and NH_3 production (Carulla et al., 2005; Tavendale et al., 2005; Grainger et al., 2009). Thus, there is a need to investigate whether tannin supplements in cattle diets influence N dynamics and CH_4 emissions during composting. Addition of mature compost, as a source of nitrite oxidizing bacteria (NOB) to actively composting swine manure, has also been shown to reduce N_2O emissions (Fukumoto et al., 2006; Fukumoto and Inubushi, 2009), and also needs to be investigated.

Our goals were to evaluate including corn DDGS, with or without condensed tannin (CT) supplementation, in cattle diets on N excretion and stability during manure storage and composting; and CO_2, CH_4 and N_2O emissions during manure composting. Addition of NOB to mitigate compost N_2O emission was also investigated. We hypothesized that adding DDGS to cattle diets would increase manure and compost N content and result in higher N_2O emissions during composting. We further hypothesized that adding CT to a diet containing DDGS would reduce manure NH_4^+ and increase total N content, thereby reducing N_2O emissions associated with feeding DDGS to cattle.

2. Materials and methods

2.1. Experimental treatments

The study was conducted from 6 July 2009 to 22 February 2010 in a semi-arid climate at the Agriculture and Agri-Food Canada Research Center in Lethbridge, AB, Canada. The composting experiment included manure from feedlot cattle fed three finishing diets being: (1) Check, CK: typical diet containing 860 g barley grain, 90 g barley silage, and 50 g supplement/kg dry matter (DM), (2) DDGS: diet containing 400 g DDGS/kg DM replacing barley grain, and (3) DDGS + CT: diet similar to (2), but with the addition of CT extract from *Acacia mearnsii* (black wattle tree) at 25 g/kg DM. The CT had a pH of 4.6 pH, 583 g/kg C and 36.2 g/kg N, 270 mg/kg NaHCO$_3$-extractable P, and 282 and 20 mg/kg KCl-extractable NH_4^+-N and NO_3^--N, respectively.

2.2. Manure and compost windrow management

Manure was stored in unstocked feedlot pens for 14 days from the end of the feeding experiment on 6 July 2009 until the start of the composting experiment. The composting experiment consisted of 56 days of initial composting (20/21 July to 14 September 2009; Phase1), followed by addition of mature cattle compost and a further 57 days of composting (15/17 September 2009 to 10 November 2009; Phase 2) and 104 days of compost curing (11 November 2009 to 22 February 2010; Phase 3).

On composting day 0, straw bedded manure was removed from pens and formed into open windrows on an open clay pad with two replicates/treatment in a completely randomized design. Windrows averaged 11.1 m length × 3.2 m width for CK, 14.0 m length × 3.4 m width for DDGS and 15.3 m length × 3.7 m width for DDGS + CT, and all were 1.5 m high. Windrows were turned with a tractor pulled windrow turner (EarthSaver model, Fuel Harvesters Equipment Inc., Midland, TX, USA) on composting day 8, 22 and 36.

On composting day 56, windrows from each treatment were thoroughly mixed and divided into four portions. Two portions were mixed with 100 kg/tonne (DM basis) of mature compost as a source of NOB whereas the other portions were left as is. All portions were moved into individual composting bins of 2.3 m length × 2.4 m width × 1.8 m height, in a completely randomized design. A slotted wood pallet of 0.15 m in height was placed in the bottom of each bin to allow airflow with barley straw bales forming the walls. The pallets were covered with a thin layer of straw before loading the compost into the bins. Each compost bin contained about 6.2 tonnes of dry material (DM) of compost materials. The mature compost used at the start of Phase 2 had 0.30 g/g moisture, 396.3 g/kg C, 17.6 g/kg N, 288 mg/kg NH_4^+-N and 1244 mg/kg NO_3^--N.

2.3. Temperature monitoring

Temperature probes equipped with sensors at 60, 90 and 120 cm depths were inserted into each windrow and bin to monitor temperature throughout the experiment. Thermocouples were connected to a data logger (Sciemetric, Nepean, ON, Canada) and temperature was recorded every 20 min and averaged to give mean daily values. The temperature measurement devices were installed when compost windrows were formed and were removed just before each turning, and reinstalled immediately thereafter. Daily air temperature and precipitation were also monitored and recorded.

2.4. Manure properties determination

Solid manure samples, consisting of a mixture of urine, feces, straw bedding and soil particles, were collected from the pens at the end of the feeding experiment and at the initiation of composting. At the end of the feeding experiment, two composites of 1 kg (wet weight) samples were collected from each pen (4 pens per treatment) at 5 locations.

Windrows were formed by combining manure from 4 replicate pens for each treatment. Ten manure samples (400 g wet weight) were collected from each windrow at the start of composting resulting in 20 samples/treatment. Solid compost samples were collected at the end of Phase 1, at the initiation and end of Phase 2, and at the end of Phase 3. Compost samples (~400 g wet weight) were collected at 0, 15, 30, 60, 100 and 120 cm depths. The last sample was taken from the bottom of the compost windrow, and the depth varied because the windrow height shrank with time of composting. Samples from each depth were manually homogenized and divided into 3 portions for analysis.

One portion was used to determine water soluble N (NH_4^+-N + NO_3^--N) at a 1:4 manure to deionized water ratio. Water soluble N content was measured in an autoanalyzer (Model AA3, Bran + Luebbe, Nordersted, Germany). The second portion was used to determine moisture content after drying at 60 °C for at least 4 days. The third portion was frozen at −40 °C, then freeze-dried using a Virtis model 25XL (The Virtis Company, Gardiner, NY, USA) to avoid possible NH_3 volatilization loss (Mahimairaja et al., 1990). Freeze dried samples were coarsely (<2 mm) and finely (0.150 mm) ground and used for total C and total N determination. The total C and total N contents were determined using a NA 1500 Series 2 Carlo Erba Instrument (Rodano, Milan, Italy). Results are the average of the compost samples collected at different depths. Data are reported on a 60 °C DM basis.

2.5. Gas collection and analysis

Greenhouse gas (GHG) surface fluxes were measured weekly during Phase 1 and 2 composting and every 2 weeks during Phase 3. Surface flux gas samples were collected using a vented static chamber technique similar to Hutchinson and Mosier (1981) as modified by Hao et al. (2001). Surface flux samples were collected from each composting windrow at 0, 5, 10, 20 and 30 min after the chambers were placed on the peak of the windrow surface. Each gas sample (11 mL) was extracted with an air-tight syringe and injected into a 5.9 mL pre-evacuated, septum-sealed, vial (Exetainer; Labco Limited, High Wycombe, Buckinghamshire, UK). Samples were analyzed for CO_2, CH_4 and N_2O contents using a gas chromatograph (Varian 3800; Varian Instruments, Walnut Creek, CA, USA) equipped with an electron capture detector, a flame ionization detector, a thermal conductivity detector, and a micro-gas chromatograph (Varian 4900) equipped with an electron capture detector and a thermal conductivity detector.

The concentration *versus* time relationships for each GHG in each chamber were fitted with a second-order polynomial equation for each sampling time (SAS, 2008), and the flux at $t = 0$ was calculated by taking derivatives of the second-order polynomials (Hao et al., 2001). Cumulative emissions were approximated by assuming that daily fluxes represented the average for each period. Cumulative GHG emissions over each composting Phase were expressed as kg/tonne manure and/unit initial manure C and N.

2.6. Statistical analysis

Average bi-weekly temperatures were calculated based on daily temperatures at sampling depths of 60, 90 and 120 cm, and analyzed using Proc MIXED in SAS with treatment, sampling week, and treatment × sampling week in the model as fixed effects and replicate × treatment as a random effect. Sampling week was treated as a repeated measure to account for potential correlations and different variances among weeks. The manure/compost properties and GHG data were also analyzed using MIXED with treatment (*i.e.*, manure source), sampling date, and treatment × sampling date in the model as fixed effects and replicate × treatment as a random effect. Sampling date was treated as a repeated measure to account for potential correlations and different variances between phases. Various variance-covariance matrices were fitted and the one with the lowest Akaike's Information Criterion was used for the final analysis. The procedure UNIVARIATE was used to check residuals for normality and potential outliers. When treatment effects were not significant, data were pooled and re-analyzed. When any of the fixed effects was significant (P<0.05), means comparisons were conducted using a protected LSD test (P<0.05). Relationships between cumulative N_2O emissions and NH_4^+ and NO_3^- contents during composting were investigated using correlation analysis.

3. Results

3.1. Weather conditions

During the experiment, the daily air temperature varied considerably with mean, maximum and minimum air temperatures of 18.0, 23.9 and 7.9 °C during Phase 1; 7.1, 24.0, and −6.9 °C during Phase 2 and; −5.6, 9.3 and −27.7 °C during Phase 3 (Fig. 1a). During the same period, precipitation was 93.7, 53.2 and 69.1 mm, respectively.

3.2. Compost windrow temperatures

During Phase 1 composting, there was considerable variation in daily windrow temperatures, especially at the 60 cm depth (Fig. 1a). At the start of Phase 2 composting, there was an immediate increase in temperature for all treatments with
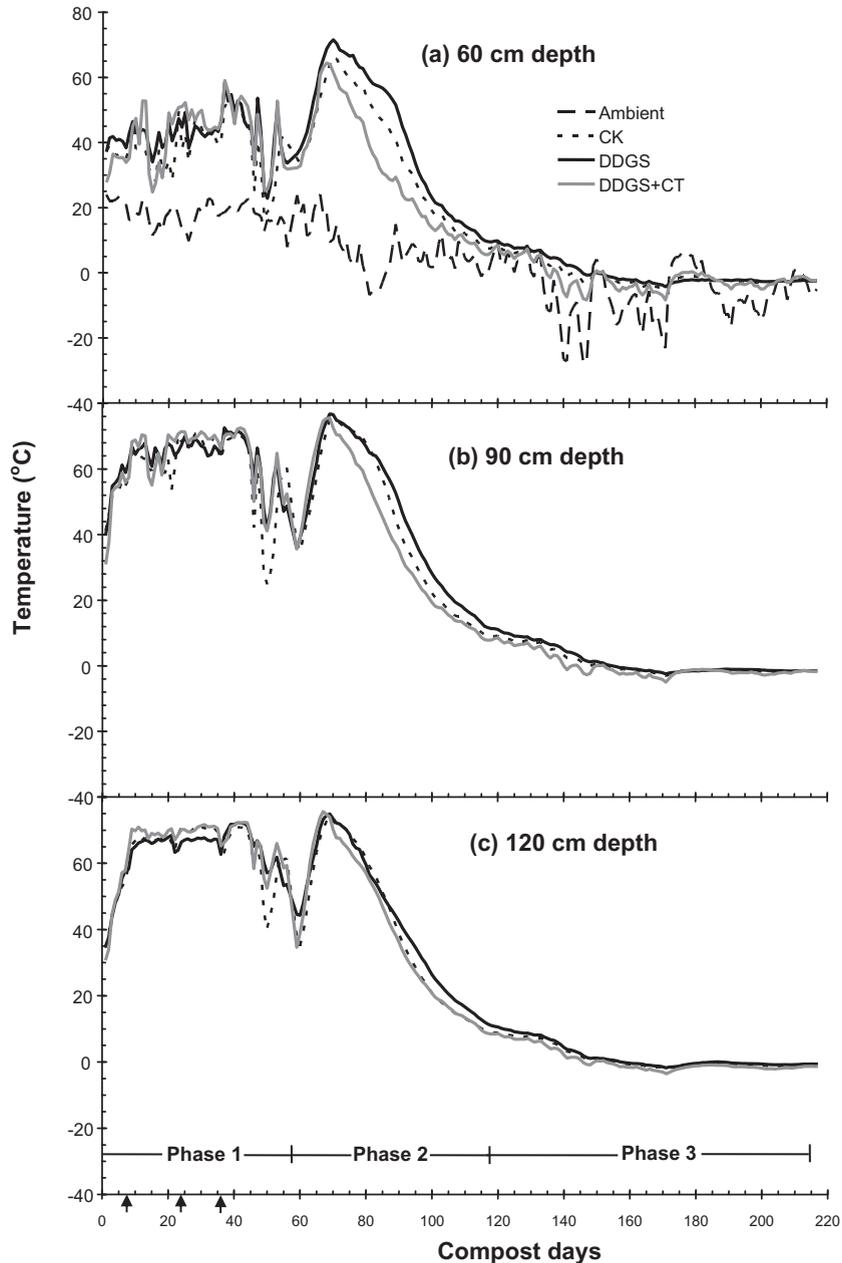

Fig. 1. Mean daily air and compost (60, 90, and 120 cm depths) temperatures during Phases 1 (Day 0–56), 2 (Day 57–113) and 3 (Day 114–217) composting. Arrows indicate windrow turning dates.

Table 1
Compost temperature (°C) responses to manure source during composting.

Week	Treatment			P		
	CK	DDGS	DDGS + CT	Treatment (T)	Week (W)	T × W
Phase 1[a]						
1–2	50.1 C[b]	52.3 C	51.2 B	0.453	<0.001	0.001
3–4	56.2 B	58.2 B	59.3 A			
5–6	61.2 AB	61.5 AB	63.1 A			
7–8	47.0 C	52.4 C	52.7 B			
Phase 2						
9–10	58.1 B	60.8 AB	58.8 A			
11–12	66.6 a A	64.8 a A	52.6 b B			
13–14	33.8 ab D	39.8 a D	30.0 b C			
15–16	15.4 E	18.7 E	16.3 D			
Phase 3						
17–18	8.5 F	10.1 F	10.9 E			
19–20	5.5 F	6.6 F	6.3 F			
21–22	0.4 G	1.4 G	0.6 G			
23–24	−1.7 G	−1.2 G	−2.0 G			
25–26	−1.6 G	−1.7 G	−1.2 G			
27–28	−1.1 G	−1.0 G	−1.9 G			
29–30	−1.7 G	−1.4 G	−2.5 G			
31	−1.4 G	−1.4 G	−2.0 G			

[a] Phase 1: Day 0–56; Phase 2: Day 57–113; Phase 3: Day 114–217.
[b] Numbers in a row followed by different lowercase letters indicate a treatment effect, while numbers in a column followed by different upper case letters indicate a sampling week effect at P<0.05 based on protected LSD test.

values peaking after 14 days (compost day 70). Maximum daily temperatures in compost reached 77 °C at all depths (Fig. 1). During Phase 3, temperatures decreased at all depths and were reflective of ambient temperature (Fig. 1).

Addition of mature compost as a possible source of NOB caused no changes in compost temperature, and so data were pooled and re-analyzed (Table 1). Average bi-weekly compost (windrow bin) temperatures were affected by sampling week (P<0.001), and treatment and sampling week interactions (P=0.001), but not by treatment (Table 1). Bi-weekly temperatures in CK (66.6 °C) and DDGS (64.8 °C) treatments were (P<0.05) higher than values in DDGS + CT (52.6 °C) for weeks 11–12 while values in DDGS (39.8 °C; P<0.05) were similar to CK (33.8 °C), but higher than DDGS + CT (30.3 °C) for weeks 13–14 during Phase 2 composting. There were no temperature differences among treatments in all other weeks in Phase 2 and all weeks in Phases 1 and 3. For all CK and DDGS treatments, the highest bi-weekly temperatures (P<0.05) were, in order of weeks, 3–6, 9–12 > 1–2, 7–8 > 13–14 > 15–16 > 17–20 > 21–31. In contrast, the bi-weekly compost temperature for DDGS + CT were (P<0.05), in order of weeks, 3–6, 9–10 > 1–2, 7–8, 11–12 > 13–14 > 15–16, 17–18 > 19–20 > 21–31.

3.3. Manure and compost properties

Addition of mature compost as a possible source of NOB caused no changes in moisture, total C and total N contents, C/N ratio, and NH_4^+ and NO_3^- contents for all sampling dates. Thus, data were pooled within treatments that received no mature compost and are in Tables 2 and 3. Moisture content was affected by sampling date, but not treatment or the interaction between sampling date and treatment. Moisture contents were similar among all treatments for each sampling date, but decreased (P<0.001) with time (Table 2).

The total C and total N contents and C/N ratios were affected (P<0.05) by both treatment and sampling date, but not their interaction (except total N; Tables 2 and 3). Averaged across all sampling dates, C contents were higher, and C/N ratios were lower, for the DDGS + CT treatment than the CK and DDGS treatments while, averaged across all treatments, C and C/N ratios decreased with time (Table 2). The C content in the feedlot pen manure was 260.2 g/kg decreasing to 118.8 g/kg by the end of the compost experiment. In contrast, the C/N ratio declined only slightly from 13.0 to 11.0.

The total N contents were (P=0.001) in the order of CK (16.4 g/kg) < DDGS (21.2 g/kg) < DDGS + CT (25.0 g/kg) at the end of feeding experiment (Table 3). However, differences among treatments narrowed with time and values for both CK and DDGS (9.8 g/kg) were lower (P=0.001) than DDGS + CT (13.0 g/kg) at the end of the composting experiment. The total N content decreased with time depending on treatment. Total N content decreased (P=0.001) most for DDGS (54%), followed by DDGS + CT (48%) and CK (40%).

The NH_4^+-N content was affected (P<0.05) by treatment, sampling date and their interaction (Table 3). The NH_4^+-N content from DDGS was (P=0.015) higher than CK and DDGS + CT treatments at the end of the feeding experiment. Inclusion of CT extract at 25 g/kg of dietary DM (treatment DDGS + CT) reduced (P=0.015) NH_4^+-N in manure by 41.1% compared to the DDGS diet. At the start of windrow construction and at the end of Phase 1 composting at 56 days, the NH_4^+-N content in DDGS and DDGS + CT were similar and both were higher (P=0.015) than the CK treatment. For the remainder of the sampling dates, the NH_4^+-N content was highest in DDGS + CT, followed by DDGS with

Table 2
Moisture, total C, C/N ratio and NO_3^--N content of manure and compost materials.

Properties[a]			P		
			Treatment (T)	Phase (P)	T × P
Moisture (g/g)	Treatment		0.722	<0.001	0.793
	CK	0.352			
	DDGS	0.354			
	DDGS + CT	0.348			
	Phase				
	Feeding expt: end	0.626 A[b]			
	Phase 1: initial	0.554 B			
	end	0.323 C			
	Phase 2: initial	0.241 D			
	end	0.219 D			
	Phase 3: end	0.232 D			
Total C (g/kg DM)	Treatment		0.004	<0.001	0.926
	CK	165.5 B			
	DDGS	163.0 B			
	DDGS + CT	180.8 A			
	Phase				
	Feeding expt: end	260.3 A			
	Phase 1: initial	238.0 A			
	end	141.8 B			
	Phase 2: initial	127.4 B			
	end	132.0 B			
	Phase 3: end	118.8 B			
C/N ratio	Treatment		<0.001	<0.001	0.112
	CK	12.9 A			
	DDGS	12.0 A			
	DDGS + CT	10.6 B			
	Phase				
	Feeding expt: end	13.0 A			
	Phase 1: initial	13.7 A			
	end	11.4 B			
	Phase 2: initial	10.9 B			
	end	11.1 B			
	Phase 3: end	11.0 B			
NO_3^--N (mg/kg DM)	Treatment		0.666	<0.001	0.179
	CK	44.7			
	DDGS	48.0			
	DDGS + CT	55.4			
	Phase				
	Feeding expt: end	17.8 C			
	Phase 1: initial	36.1 BC			
	end	21.2 C			
	Phase 2: initial	116.9 A			
	end	36.4 B			
	Phase 3: end	53.1 B			

[a] Data reported on a DM basis.
[b] Different uppercase letter in a column within each property indicate treatment and phase effects at P<0.05 based on protected LSD test.

the lowest in the CK treatment. The exception was at the end of Phase 2, when there were no differences among treatments.

The NH_4^+-N content in all treatments decreased with time during manure storage and Phase 1 composting, reaching a minimum at the start of Phase 2, then increasing until the end of the experiment. The largest reduction occurred during the 14 days storage in the feedlot pens with manure NH_4^+-N content decreasing (P=0.015) most in CK (53.6%), followed by DDGS (34.7%), while values did not change in DDGS + CT during this period. During composting Phase 1 (*i.e.,* first 56 days), there was no variation in NH_4^+-N contents with time. During Phases 2 and 3, there was an overall increase (P=0.015) in NH_4^+-N contents in all treatments.

The NO_3^--N content was not affected by treatment or the interaction between treatment and sampling date, but was affected (P<0.001) by sampling date. The NO_3^--N ranged from 10.1 to 59.5 mg/kg for all sampling dates, lower (P<0.001) than values at the start of Phase 2 (94.1–138.1 mg/kg; Table 2).

Table 3
Total N and NH_4^+-N contents of manure and compost materials.

Properties[a]	Phase	Treatment			P[b]		
		CK	DDGS	DDGS + CT	T	P	T × P
Total N (g/kg DM)	Feeding expt: end	16.4 c A [c]	21.2 b A	25.0 a A	< 0.001	<0.001	0.001
	Phase 1: initial	16.7 b A	14.9 b B	21.3 a B			
	end	11.2 b B	11.9 ab CD	14.7 a C			
	Phase 2: initial	10.6 b B	10.8 b CD	13.9 a C			
	end	10.3 b B	12.9 a BC	12.8 a C			
	Phase 3: end	9.8 b B	9.8 b D	13.0 a C			
NH_4^+-N (mg/kg DM)	Feeding expt: end	1189 b A	2396 a A	1411 b AB	< 0.001	<0.001	0.015
	Phase 1: initial	551 b BC	1565 a B	1277 a AB			
	end	509 b BC	1374 a B	1427 a AB			
	Phase 2: initial	312 c C	833 b C	1165 a B			
	end	1073 AB	1156 BC	1295 AB			
	Phase 3: end	1194 c A	1423 b B	1609 a A			

[a] Data reported on a DM basis.
[b] T, treatment; P, phase (sampling date).
[c] For each property, numbers in a row followed by different lowercase letters indicate treatment effect, while numbers in a column within each property followed by different uppercase letters indicate sampling date effect at P<0.05 based on protected LSD test.

3.4. CO_2, CH_4 and N_2O emissions

Similar to compost properties, addition of mature compost as a source of NOB had no effect on any of GHG (Table 4). Most CO_2, CH_4 and N_2O emissions occurred during Phase 1 composting (Fig. 2 and Table 4). During Phase 1, the rate of GHG emissions varied considerably with sharp increases after each turning (day 8, 22 and 36; Fig. 2). There was also a sharp increase in GHG emissions upon initiation of Phase 2 (Fig. 2), with the maximum occurring about 6 days after Phase 2 started (day 63).

The GHG emissions were only affected (P<0.001) by sampling date, not by treatment or the treatment × sampling date interaction (Table 4). There were no differences in the amount of CO_2, CH_4 and N_2O emissions among treatments during any composting Phase when emissions were reported in terms of manure DM or initial manure C and N (Table 4). Cumulative emissions in Phase 1 for all treatments were 90.70, 5.30 and 0.09 kg/tonne DM for CO_2-C, CH_4-C and N_2O-N, respectively and were higher (P<0.001) than values from Phase 2 (4.59, 0.07 and 0.002 kg/tonne DM). Emissions were negligible during Phase 3 (0.00–0.06 kg/tonne DM; Table 4). Cumulative N_2O emissions were not related to NH_4^+ and NO_3^- contents during composting.

Table 4
Cumulative CO_2-C, CH_4-C and N_2O-N emissions during Phases 1, 2, and 3 composting.

GHG emission[a]	Phase[b]	Treatments			P[c]		
		CK	DDGS	DDGS + CT	T	P[d]	T × P
CO_2-C (kg C/tonne DM)	Phase 1	100.27	82.51	89.31	0.505	<0.001	0.198
	Phase 2	3.31	5.12	5.35			
	Phase 3	0.04	0.07	0.07			
CH_4-C (kg C/tonne DM)	Phase 1	5.74	5.68	4.48	0.393	<0.001	0.567
	Phase 2	0.03	0.16	0.01			
	Phase 3	<0.00	<0.00	<0.00			
N_2O-N (kg N/tonne DM)	Phase 1	0.077	0.088	0.107	0.433	<0.001	0.640
	Phase 2	0.002	0.002	0.002			
	Phase 3	<0.000	<0.000	<0.000			
CO_2-C (kg C/tonne C)	Phase 1	410.25	380.42	353.14	0.282	<0.001	0.170
	Phase 2	13.58	23.59	21.13			
	Phase 3	0.16	0.32	0.29			
CH_4-C (kg C/tonne C)	Phase 1	23.49	26.18	17.72	0.214	<0.001	0.314
	Phase 2	0.13	0.75	0.04			
	Phase 3	<0.00	<0.00	<0.00			
N_2O-N (kg N/tonne N)	Phase 1	4.616	5.870	4.999	0.562	<0.001	0.778
	Phase 2	0.110	0.154	0.104			
	Phase 3	0.001	0.001	0.004			

[a] GHG emissions are reported on both manure DM and initial total C or total N basis.
[b] Phase 1: Day 0–56; Phase 2: Day 57–113; Phase 3: Day 114–217.
[c] T, treatment; P: Phase (sampling date).
[d] Phase affected GHG emissions with CO_2 emission from Phase 1 > Phase 2 > Phase 3; CH_4 emission from Phase 1 > Phase 2 = Phase 3; N_2O emission from Phase 1 > Phase 2 = Phase 3 at P<0.05 based on the protected LSD test.
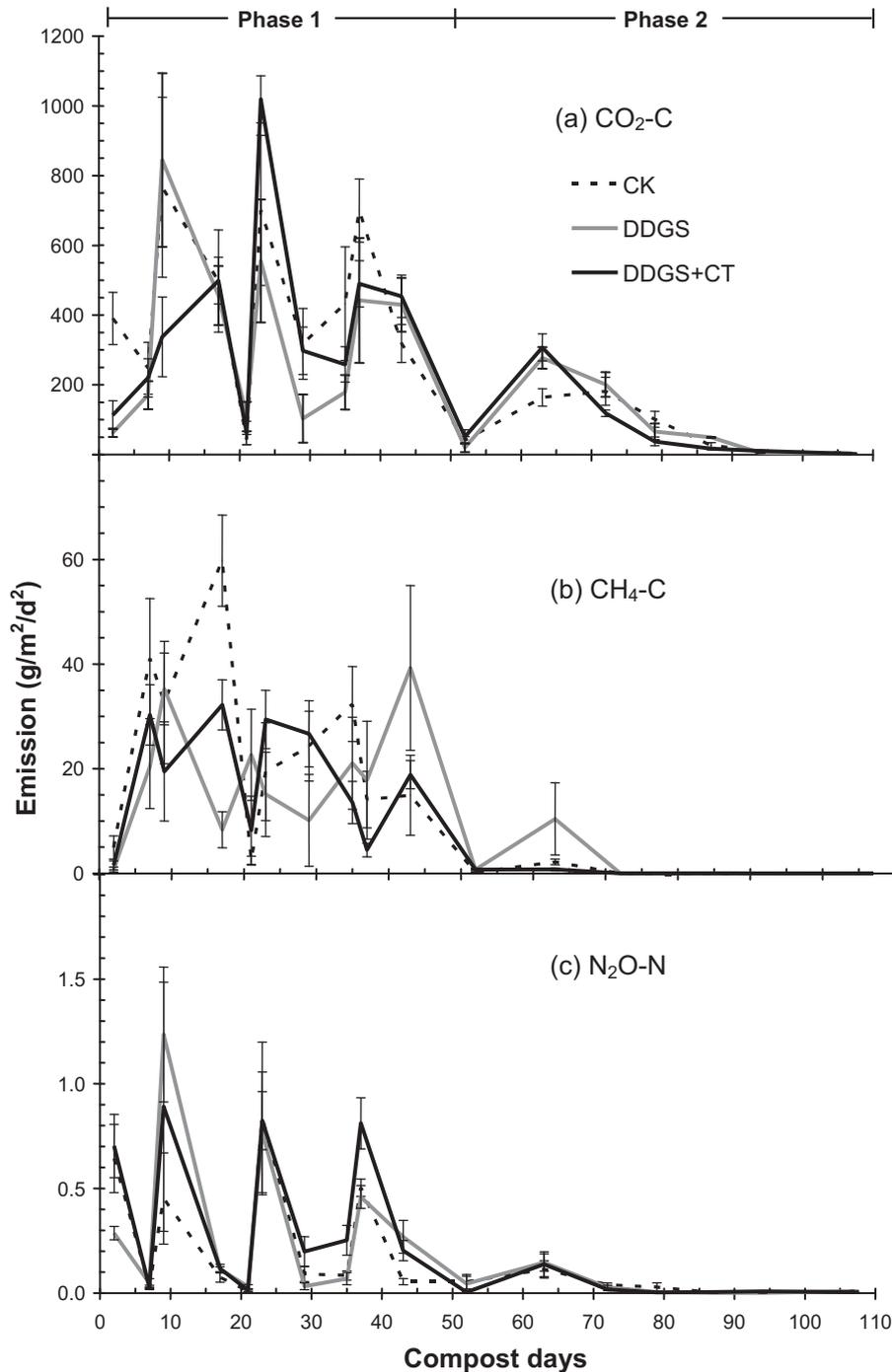
Fig. 2. Greenhouse gas (CO_2, CH_4, and N_2O) surface fluxes during Phases 1 (Day 0–56) and 2 (Day 57–113) composting (GHG emission data from Phase 3 (Day 114–217) are not presented as values were negligible). Bars indicate SE and arrows indicate windrow turning dates.

4. Discussion

The high level of DDGS (400 g/kg DM) in the cattle diet in our study is consistent with the high end of rates used in practice, although 200–300 g/kg DM are commonly used by local feedlot operators. Quite often, the decision to include DDGS and its level of inclusion is driven by the relative cost of DDGS compared to traditional grains as the prices for both feedstuffs fluctuate depending on market supply and demand. Hao et al. (2009b) pointed out that feeding DDGS at 400 g/kg DM or more to finishing feedlot cattle could not be recommended from

an environmental perspective due to very high levels of N and P excreted in manure from beef cattle fed such a diet.

4.1. Compost windrow temperatures

The similar windrow temperatures among treatments at the three depths during Phase 1 most likely reflect similar moisture levels among treatments, a factor which affects microbial activity during composting and, therefore, temperature (Peigné and Girardin, 2004). These moisture levels are considered optimal for composting (Tiquia et al., 1996) and likely account for the high temperatures in our study. During Phase 2, the lower temperatures in the DDGS + CT than in DDGS and CK treatments may be related to the higher NH_4^+-N content in DDGS + CT than in DDGS and CK at the beginning of Phase 2, a factor that could have inhibited microbial activity (Bustamante et al., 2008). The increase in temperature at the beginning of Phase 2 (Fig. 1) in all treatments was probably caused by constant airflow through the wood slotted platform at the bottom of each compost bin. During Phase 3, there was a substantial decrease in temperature at all depths in all treatments reflecting reduced microbial activity.

4.2. Manure and compost properties

The higher total N and NH_4^+-N contents in DDGS than CK fresh manure reflects the higher level of crude protein in DDGS based diets than in grain based diets. This is consistent with a previous study which reported increases in feces N and manure NH_4^+ with increasing wheat DDGS levels in the diet (Hao et al., 2009b). In our study, addition of CT to the DDGS diet increased total N content and reduced NH_4^+-N in fresh manure compared to the DDGS treatment, thereby supporting our hypothesis. Because most NH_4^+-N in manure originates from urea in urine, the reduction in NH_4^+-N and increase in total N contents likely reflects CT causing a shift in N excretion from urine to feces. This shift in N excretion in ruminants fed tannin supplemented diets has been noted in sheep and dairy cattle (Śliwiński et al., 2002, 2004; Carulla et al., 2005; Hess et al., 2006; Powell et al., 2009), as tannin reduces ruminal NH_3 content by either inhibiting growth of ruminal proteolytic bacteria (Patra and Saxena, 2009) and/or forming complexes with plant proteins (Makkar, 1993; Reed, 1995; Halvorson et al., 2009). The higher C content in DDGS + CT fresh manure than in DDGS and CK may further indicate that dietary CT reduces ruminal fiber digestion by formation of CT-cellulose complexes (Makkar et al., 1995a) and/or reduction in the activity of ruminal cellulolytic bacteria (McSweeney et al., 2001). Despite a reduction in total C and total N contents for all treatments during manure storage and composting, total C and total N contents in DDGS + CT treatment in the final compost were still higher than values in the DDGS and CK treatments. The higher C and N contents and lower C/N ratio in DDGS + CT than in the other treatments throughout the composting experiment mainly reflects differences in the manure produced during the feeding experiment. Decomposition of organic matter is responsible for decreases in C and N contents over the experimental period, and decreases in the C/N ratio with time reflected higher losses of C versus N.

The reductions in NH_4^+-N contents from the DDGS and CK treatments during the 14 days of storage, and the first 56 days of composting, were likely due to NH_4^+ conversion to NH_3 and subsequent volatilization, which causes odors (Varel, 2002) and adverse environmental effects (Pitcairn et al., 2002; Hao et al., 2009a). However, there were no changes in NH_4^+-N content for the DDGS + CT treatment. The higher NH_4^+-N content in the final compost for DDGS + CT versus the DDGS and CK treatments probably reflects the ability of CT to form complexes with N, thereby reducing its solubility (Halvorson et al., 2009) and/or effects of CT on inhibiting urease activity, which would reduce N loss as NH_3 (Śliwiński et al., 2004). Similar results have been reported for short-term storage of manure from dairy cows fed tannin supplemented diets (Śliwiński et al., 2004; Misselbrook et al., 2005). However, our study is apparently the first to investigate effects of dietary CT on N dynamics in manure under long term composting. Further studies are necessary to investigate transformations of dietary CT in the ruminant digestive tract and during manure composting.

The similar NO_3^--N content among treatments appears to indicate that CT did not affect nitrification which produces NO_3^-. Nitrification increases NO_3^- concentration during composting (Tiquia et al., 2002; Hao et al., 2004). However, in our study the NO_3^--N content was similar among composts and the final compost NO_3^--N content was low. High temperatures at the beginning of Phase 2 (Fig. 1) combined with the high NH_4^+-N content (Table 3) may have inhibited activity and growth of nitrifying bacteria (Angelidaki and Ahring, 1994; Bustamante et al., 2008). The slight increase in NO_3^--N content at the start of Phase 2 was likely caused by addition of 100 kg/tonne mature compost as a NOB source as the NO_3^--N content in the added mature compost (1124 mg/kg) was much higher than values at the end of Phase 1 composting of 21.2 mg/kg.

4.3. CO_2, CH_4 and N_2O emissions

Adding mature swine compost to fresh swine manure has successfully reduced N_2O emissions by reducing NO_2^- accumulation in a closed composting system (Fukumoto et al., 2006; Fukumoto and Inubushi, 2009). However in our study adding mature cattle compost to windrows at 100 kg/tonne as a source of NOB failed to affect N_2O emission. Since most N_2O emission occurred in Phase 1, prior to the NOB addition, the low N_2O emissions for all treatments in Phase 2 suggest that it is possible there is no NO_2^- accumulation. Thus, adding NOB at this time may have no impact on N_2O emissions. It is possible that mature compost should have been added earlier in order to have an effect on NO_2^- accumulation.

Most GHG emissions occurred in the initial 56 days of composting, reflecting the period of highest microbial activity and organic matter decomposition. In our study, the higher daily CO_2 and CH_4 surface fluxes for CK than DDGS treatment at initial stages of composting, followed by the opposite pattern as composting progressed, is consistent with previous results reported on cattle manure composting from feedlot cattle fed diets containing DDGS (Hao et al., 2011). The similar cumulative CH_4 emissions among treatments suggest the mitigating effects of dietary CT on rumen CH_4 emissions (Makkar et al., 1995a) do not persist during manure composting. Condensed tannins inhibit microbial activity and form complexes with protein and cellulose, reducing rumen CH_4 emission (Makkar, 1993; Makkar et al., 1995a). Although rumen microbes apparently do not degrade CT (Makkar et al., 1995b), it is possible that the level of dietary CT used in this study was too low, or the CT was complexed with protein upon excretion in the feces (Makkar, 2003). It is also possible that microbes in compost are capable of altering the biological activity of CT.

Contrary to our hypothesis, and Hao et al. (2011), adding DDGS to the diet of feedlot cattle failed to increase daily flux and cumulative N_2O emission during manure composting. The lower dietary level of DDGS (400 g/kg DM) in this study *versus* our previous study (600 g/kg DM; Hao et al., 2011) may account for this different response. Initial manure total N, NH_4^+-N and NO_3^--N contents in manure from cattle fed 600 g/kg DDGS were higher than those in our study. Feeding DDGS at 600 g/kg DM to finishing cattle is not recommended due to impaired animal growth (Gibb et al., 2008), and the high level of N excreted in manure (Hao et al., 2009a,b).

5. Conclusions

Adding mature compost as an NOB source after an initial 56 days windrow composting had no effect on final compost properties or GHG emissions. We confirmed our hypotheses that adding DDGS to cattle diets increases manure and compost NH_4^+ content and that adding CT to a diet containing DDGS reduces NH_4^+ content and increases total N content of manure and compost. Our results did not support the hypotheses that when composting manure from DDGS fed cattle that there will be higher N_2O emissions and that added dietary CT reduces N_2O emissions. Results demonstrate that substituting 400 g/kg DDGS for barley grain and adding 25 g/kg CT improves the agronomic value of cattle manure and compost as fertilizers without increasing GHG emissions.

Conflict of interest

None.

References

Aneja, V.P., Roelle, P.A., Murray, G.C., Southerland, J., Erisman, J.W., Fowler, D., Asman, W.A.H., Patni, N., 2001. Atmospheric nitrogen compounds. II. Emissions, transport, transformation, deposition and assessment. Atmos. Environ. 35, 1903–1911.
Angelidaki, I., Ahring, B.K., 1994. Anaerobic thermophilic digestion of manure at different ammonia loads: effect of temperature. Water Res. 28, 727–731.
Animut, G., Puchala, R., Goetsch, A.L., Patra, A.K., Sahlu, T., Varel, V.H., Wells, J., 2008. Methane emission by goats consuming diets with different levels of condensed tannins from lespedeza. Anim. Feed Sci. Technol. 144, 212–227.
Bustamante, M.A., Paredes, C., Marhuenda-Egea, F.C., Pérez-Espinosa, A., Bernal, M.P., Moral, R., 2008. Co-composting of distillery wastes with livestock manures: carbon and nitrogen transformations in the evaluation of compost stability. Chemosphere 72, 551–557.
Carulla, J.E., Kreuzer, M., Machmüller, A., Hess, H.D., 2005. Supplementation of *Acacia mearnsii* tannins decreases methanogenesis and urinary nitrogen in forage-fed sheep. Aust. J. Agric. Res. 56, 961–970.
Environmental Protection Agency (EPA), 2006. Global anthropogenic emissions of non-CO_2 greenhouse gases 1990–2020 (EPA Report 430-R-06-003), June 2006, 274 pp. www.epa.gov/methane/pdfs/GreenhouseGasReport.pdf.
Fukumoto, Y., Inubushi, K., 2009. Effect of nitrite accumulation on nitrous oxide emission and total nitrogen loss during swine manure composting. Soil Sci. Plant Nutr. 55, 428–434.
Fukumoto, Y., Susuki, K., Osada, T., Kuroda, K., Hanajima, D., Yasuda, T., Haga, K., 2006. Reduction of nitrous oxide emission from pig manure composting by addition of nitrite-oxidizing bacteria. Environ. Sci. Technol. 40, 6787–6791.
Gibb, D.J., Hao, X., McAllister, T.A., 2008. Effect of dried distillers' grain from wheat on diet digestibility and performance of feedlot cattle. Can. J. Anim. Sci. 88, 659–665.
Grainger, C., Clarke, T., Auldist, M.J., Beauchemin, K.A., McGinn, S.M., Waghorn, G.C., Eckard, R.J., 2009. Potential use of *Acacia mearnsii* condensed tannins to reduce methane emissions and nitrogen excretion from grazing dairy cows. Can. J. Anim. Sci. 89, 241–251.
Hao, X., Benke, M.B., Larney, F.J., McAllister, T.A., 2011. Greenhouse gas emissions when composting manure from cattle fed wheat dried distillers' grains with solubles. Nutr. Cycl. Agroecosyst. 89, 105–114.
Hao, X., Benke, M.B., Chang, C., Janzen, H.H., Clayton, G., Hill, B.R., 2009a. Spatial pattern of ammonia sorption by soil and vegetation downwind from a cattle feedlot facility. Agric. Ecosyst. Environ. 132, 39–47.
Hao, X., Benke, M.B., Gibb, D., Stronks, A., Travis, G., McAllister, T.A., 2009b. Effects of dried distillers' grains with solubles (wheat-based) in feedlot cattle diets on feces and manure composition. J. Environ. Qual. 38, 1709–1718.
Hao, X., Chang, C., Larney, F.J., 2004. Carbon, nitrogen and greenhouse gas emission during cattle feedlot manure composting. J. Environ. Qual. 33, 37–44.
Hao, X., Chang, C., Larney, F.J., Travis, G.R., 2001. Greenhouse gas emissions during cattle feedlot manure composting. J. Environ. Qual. 30, 376–386.

Halvorson, J.J., Gonzalez, J.M., Hagerman, A.E., Smith, J.L., 2009. Sorption of tannin and related phenolic compounds and effects on soluble-N in soil. Soil Biol. Biochem. 41, 2002–2010.

Hess, H.D., Tiemann, T.T., Stürm, Ch.D., Carulla, J.E., Lascano, C.E., Kreuzer, M., 2006. Effects of tannins on ruminal degradation and excretory pattern of N and implications for the potential N emission from manure. Int. Congr. Series 1293, 330–342.

Hutchinson, G.L., Mosier, A.R., 1981. Improved soil cover method for field measurement of nitrous oxide fluxes. Soil Sci. Soc. Am. J. 45, 311–316.

IPCC, 2007. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Cambridge University Press, Cambridge, UK and New York, NY, USA, 966 pp.

Krupa, S.V., 2003. Effects of atmospheric ammonia (NH_3) on terrestrial vegetation: a review. Environ. Pollut. 124, 179–221.

Leytem, A.B., Kwanyuen, P., Thacker, P., 2008. Nutrient excretion, phosphorus characterization, and phosphorus solubility in excreta from broiler chicks fed diets containing graded levels of wheat distiller's grains with solubles. Poult. Sci. 87, 2505–2511.

Mahimairaja, S., Bolan, N.S., Hedley, M.J., MacGregor, A.N., 1990. Evaluation of methods of measurement of nitrogen in poultry and animal manures. Fert. Res. 24, 141–148.

Makkar, H.P.S., 1993. Antinutritional factors in foods for livestock. Animal Production in Developing Countries, vol. 16. Brit. Soc. Anim. Prod., Occasional Publications, pp. 69–85.

Makkar, H.P.S., 2003. Effects and fate of tannins in ruminant animals, adaptation to tannins, and strategies to overcome detrimental effects of feeding tannin-rich feeds. Small Rumin. Res. 49, 241–256.

Makkar, H.P.S., Blummel, M., Becker, K., 1995a. In vitro effects and interactions between tannins and saponins and fate of tannins in the rumen. J. Sci. Food Agric. 69, 481–493.

Makkar, H.P.S., Becker, K., Abel, H.J., Szegletti, C., 1995b. Degradation of condensed tannins by rumen microbes exposed to quebracho tannins (QT) in rumen simulation technique (RUSITEC) and effects of QT on fermentation processes in the RUSITEC. J. Sci. Food Agric. 69, 495–500.

McSweeney, C.S., Palmer, B., Bunch, R., Krause, D.O., 2001. Effect of tropical forage calliandra on microbial protein synthesis and ecology in the rumen. J. Appl. Microbiol. 90, 78–88.

Misselbrook, T.H., Powell, J.M., Broderick, G.A., Grabber, J.H., 2005. Dietary manipulation in dairy cattle: laboratory experiments to assess the influence on ammonia emissions. J. Dairy Sci. 88, 1765–1777.

Patra, A.K., Saxena, J., 2009. Dietary phytochemicals as rumen modifiers: a review of the effects on microbial populations. Antonie van Leeuwenhoek 96, 363–375.

Peigné, J., Girardin, P., 2004. Environmental impacts of farm-scale composting practices. Water Air Soil Pollut. 153, 45–68.

Pitcairn, C.E.R., Skiba, U.M., Sutton, M.A., Fowler, D., Munro, R., Kennedy, V., 2002. Defining the spatial impacts of poultry farm ammonia emissions on species composition of adjacent woodland groundflora using Ellenberg Nitrogen Index, nitrous oxide and nitric oxide emissions and foliar nitrogen as marker variables. Environ. Pollut. 119, 9–21.

Powell, J.M., Broderick, G.A., Grabber, J.H., Hymes-Fecht, U.C., 2009. Effects of forage protein-binding polyphenols on chemistry of dairy excreta. J. Dairy Sci. 92, 1765–1769.

Reed, J.D., 1995. Nutritional toxicology of tannins and related polyphenols in forage legumes. J. Anim. Sci. 73, 1516–1528.

RFA, 2008. Feeding the Future: The Role of the U.S. Ethanol Industry in Food and Feed Production. Renewable Fuels Association, Washington, DC, USA, www.ethanolrfa.org/objects/documents/1913/feed_co-products.pdf.

SAS Institute Inc., 2008. SAS OnlineDoc 9.1.3. SAS Institute Inc., Cary, NC, USA.

Śliwiński, B.J., Kreuzer, M., Sutter, F., Machmüller, A., Wettstein, H.-R., 2004. Performance, body nitrogen conversion and nitrogen emission from manure of dairy cows fed diets supplemented with different plant extracts. J. Anim. Feed Sci. 13, 73–91.

Śliwiński, B.J., Kreuzer, M., Wettstein, H.-R., Machmüller, A., 2002. Rumen fermentation and nitrogen balance of lambs fed diets containing plant extracts rich in tannins and saponins, and associated emissions of nitrogen and methane. Arch. Anim. Nutr. 56, 379–392.

Tavendale, M.H., Meagher, L.P., Pacheco, D., Walker, N., Attwood, G.T., Sivakumaran, S., 2005. Methane production from in vitro rumen with *Lotus pedunculatas* and *Medicago sativa*, and effects of extractable condensed tannin fractions on methanogenesis. Anim. Feed Sci. Technol. 123–124, 403–419.

Tiquia, S.M., Tam, N.F.Y., Hodgkiss, I.J., 1996. Microbial activities during composting of spent pig-manure sawdust litter at different moisture contents. Bioresour. Technol. 55, 201–206.

Tiquia, S.M., Wan, J.H.C., Tam, N.F.Y., 2002. Dynamics of yard trimmings composting as determined by dehydrogennase activity, ATP content, arginine ammonification, and nitrification potential. Process Biochem. 37, 1057–1065.

Varel, V.H., 2002. Livestock manure odor abatement with plant-derived oils and nitrogen conservation with urease inhibitors: a review. J. Anim. Sci. 80 (E. Suppl. 2), E1–E7.