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Manure Flushing vs. Scraping in Dairy Freestall Lanes Reduces Gaseous Emissions

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Abstract: The objective of the present study was to mitigate ammonia (NH_3), greenhouse gases (GHGs), and other air pollutants from lactating dairy cattle waste using different freestall management techniques. For the present study, cows were housed in an environmental chamber from which waste was removed by either flushing or scraping at two different frequencies. The four treatments used were (1) flushing three times a day (F3), (2) flushing six times a day (F6), (3) scraping three times a day (S3), and (4) scraping six times a day (S6). Flushing freestall lanes to remove manure while cows are out of the barn during milking is an industry standard in California. Gas emissions were measured with a mobile agricultural air quality lab connected to the environmental chamber. Ammonia and hydrogen sulfide (H_2S) emissions were decreased ($p < 0.001$ and $p < 0.05$) in the flushing vs. scraping treatments, respectively. Scraping increased NH_3 emissions by 175 and 152% for S3 and S6, respectively vs. F3. Ethanol (EtOH) emissions were increased ($p < 0.001$) when the frequency of either scraping or flushing was increased from 3 to 6 times but were similar between scraping and flushing treatments. Methane emissions for the F3 vs. other treatments, were decreased ($p < 0.001$). Removal of dairy manure by scraping has the potential to increase gaseous emissions such as NH_3 and GHGs.

Keywords: ammonia emissions; dairy cow; flushing; freestall barn; scraping

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1. Introduction

The United States has more than 14 million dairy animals that produce approximately 145,000,000 ton of manure per year and 1,663,735 ton of nitrogen per year [1]. California is the leading producer of fluid milk and produces 20% of all dairy products in the U.S., with the majority of production concentrated in the San Joaquin Valley. This large concentration of dairy cattle contributes to one of the worst air quality regions in the U.S. [2–4]. Dairies are a source of air pollutants such as NH_3, a precursor to particulate matter formation and smog forming volatile organic compounds (VOC) [5].

In 2016, the California Air Resources Board (CARB) released the Proposed Short Lived Climate Pollutant (SLCP) Reduction Strategy to reduce CH_4 emissions from dairy manure (i.e., urine and feces) management. In response to the SLCP reduction strategy, Senate Bill 1383 was passed in 2016, which requires a reduction of CH_4 emissions by 40% below 2013 levels by 2030. The majority of these reduction strategies consist of dairies converting from current liquid manure storage systems such as lagoons to dry manure storage, which would utilize scraping rather than flushing of freestall barns where the cows are housed. This conversion of manure management would eliminate so-called manure storage lagoons, which are considered to be a large CH_4 contributor, and encourages the use of anaerobic digesters to handle scraped manure [6].

The plan of action proposed by CARB to reduce CH_4 emissions from manure may have unintended consequences affecting other criteria pollutants, such as NH_3 emissions from dairies. Ammonia is a precursor to the formation of $PM_{2.5}$, which is a small aerosol that can subsist in the atmosphere for as long as 15 days. When $PM_{2.5}$ is inhaled it can carry pathogens that infiltrate the alveoli of the lungs and enter the blood stream, causing illness and respiratory disease [7,8]. This is problematic for the San Joaquin Valley as it exceeds the regulatory limits for $PM_{2.5}$ and ozone (O_3) and is classified as a serious nonattainment area by the California Air Resources Board [9].

Within livestock production, dairies were identified as the largest source of NH_3 emissions in California [10]. Sheppard et al. (2011) produced a model simulation that suggests up to 53% of the excreted total ammonia nitrogen (TAN) from a lactating cow will be emitted to the atmosphere as NH_3 during the housing, storage, and land spreading of manure [11]. Harper et al. (2009) reported estimates of excreted nitrogen (N) to be 7.6 ± 1.5% of input feed N based on data from three different dairies in Wisconsin from barns, manure treatment, and storage [12].

Further research is needed to better understand the full impacts of CH_4 mitigation strategies to comply with public policy including a better understanding of the variables effecting NH_3 emissions. It was hypothesized that scraping dairy freestall lanes would increase NH_3 emissions compared to flushing. The objective of the present study was to quantify NH_3 emissions, greenhouse gases, and other air pollutants as a result of scraping versus flushing manure removal strategies commonly utilized in dairy freestall barns.

2. Materials and Methods

2.1. Environmental Chamber Design

The study was conducted in an environmental chamber (4.4 m × 2.8 m × 10.5 m) under an IACUC approved protocol (#18818) at the University of California, Davis, Swine Teaching and Research Center. The environmental chamber, which is designed to work for various livestock species, was equipped to house 3 dairy cows under freestall conditions. The environmental chamber has a total volume of 142 m^3, a chamber residence time of approximately 3 min at the continuous ventilation rate of 51,848 L/min, and an air exchange rate of 20 times per hour. The chamber was air conditioned and set to 20 °C to maintain cow comfort. Industry standard freestall stanchions were assembled on the west end of the chamber to allow for the animals to maintain normal resting behaviors. Feed bunks and water troughs were located on the east end of the chamber that allowed for ad libitum access. The environmental chamber was certified by the Association for Assessment and Accreditation of Laboratory Animal Care International (AAALAC). Cows were housed at the University of California, Davis's Dairy Teaching and Research Facility when emissions measurements were not being collected in the environmental chamber. Emission measurements were collected on Monday, Wednesday, and Friday over 5 and a half weeks from the three cows assigned to the chamber on each testing day. Animals were milked at 04:00 h at the dairy facility and immediately transported to the environmental chamber for the 11 h data collection followed by transportation back to the dairy for the evening milking at 16:30 h. Cows were monitored in the chamber from approximately 05:00 to 16:00 h.

2.2. Animals and Diets

Twelve multiparous lactating Holstein cows were blocked by days in milk, milk production, parity, and pregnancy status before being randomly assigned to one of four groups (n = 4). Cows were fed the standard UC Davis dairy ration ad libitum during the testing period, upon arrival at the environmental chamber. While animals were housed at the UC Davis dairy, they were fed at: 04:00, 12:00, 16:00, and 22:00 h. The diet was analyzed by Cumberland Valley Analytical Services, Inc. (Hagerstown, MD, USA) for dry matter (DM), crude protein (CP), ash, acid detergent fiber (ADF), and neutral detergent fiber (aNDF). The chemical composition and ingredients of the total mixed ration (TMR) are shown in Tables 1 and 2, respectively. During gas emissions monitoring days, feed refusals were removed at the end of the day to assess group daily feed intake while in the chamber. Cows were milked twice daily at 04:00 and 16:30 h. Milk yield records for all animals were maintained for the duration of the study. Average feed intake across treatments was 32.70 ± 7.94 kg.

Table 1. Chemical composition of the total mixed ration.

Measures	Total Mixed Ration (% DM) [1]
Crude Protein	20.4
Ash	6.85
Neutral Detergent Fiber	31.8
Acid Detergent Fiber	23.7

[1] DM = dry matter.

Table 2. Ingredients of basal total mixed ration.

Feed Ingredients	As Fed (kg/d/cow)
Grain [1]	11.91
Alfalfa Hay	11.34
Whole Cotton Seed	2.27
Almond Hulls	2.27
Strata [2]	0.1
Milk Mineral	0.34
EnerGII [3]	0.29
Salt	0.07
Wheat Hay	0.91

[1] Grain mix contained: 20.50% rolled barley, 20.50% rolled corn, 21.03% dried distillers grains, 21.96% wheat mill run, 14.48% beet pulp, and 1.53% canola meal. [2] A calcium salt of fatty acids containing a blend of palmitic, stearic, and oleic fatty acids with a 16% eicosapentaenoic acid (EPA)/docosahexaenoic acid (DHA) omega-3 fatty acids (Virtus Nutrition, Corcoran, CA, USA). [3] A calcium salt of fatty acids containing 50% palmitic and 35% oleic fatty acids (Virtus Nutrition, Corcoran, CA, USA).

2.3. Treatments

The present manure removal study was designed as a Latin square with four treatments including: (1) flushing 3 times a day (F3, Control), (2) flushing 6 times a day (F6), (3) scraping 3 times a day (S3), and (4) scraping 6 times a day (S6). Each of the treatments occurred on different data collection days for a total of 16 days. The treatments were applied three times a day, at 08:30, 12:00, and 15:30 h, or six times a day at 06:45, 08:30, 10:15, 12:00, 13:45, and 15:30 h. Flushing consisted of spraying water on the concrete floor until all of the visible manure was flushed down the drain. The scraping treatment used metal scrapers to manually clear the manure into the drain. Each manure removal treatment took approximately ten minutes to complete and clean the pen. The drain in the chamber was plugged to keep urine and feces in the chamber and sewage gases from entering the chamber during the testing period. The drain plug was removed for cleanings and replaced after.

2.4. Equipment

A mobile agricultural air quality laboratory (MAAQL) was used to measure all emissions from the environmental chamber. This MAAQL contained gas analyzers, an air sampling system, and a data acquiring system to collect real-time air emission data from the environmental chamber. The environmental chamber had one incoming and one outgoing air duct. Teflon tubing (12.7 mm ID) transported air from inside the chamber through the air duct immediately above the ceiling and into the MAAQL. The Thermo 17i $NO/NO_x/NH_3$ analyzer (Thermo Scientific, Waltham, MA, USA) was used to measure NH_3, nitric oxide (NO), and oxides of nitrogen (NO_x). Methane was measured using the Thermo 55C CH_4 analyzer (Thermo Scientific, Waltham, MA, USA). Hydrogen sulfide (H_2S) was measured using the Thermo 450i sulfur dioxide (SO_2)/H_2S analyzer (Thermo Scientific, Waltham, MA, USA). Nitrous oxide (N_2O) was measured using the Thermo 46i

N_2O analyzer (Thermo Scientific, Waltham, MA, USA). Ethanol (EtOH), carbon dioxide (CO_2), NH_3, and methanol (MeOH) were measured with the INNOVA model 1412 Photoacoustic Gas Monitor (INNOVA AirTech Instrument, Ballerup, Denmark). Table 3 shows detection limits and upper monitoring ranges of all gas analyzers. Samples were analyzed for 15 min each, beginning with the inlet air duct, and then the outlet air duct, and were repeated for the 11 h testing period.

The concentrations of N_2O, NO, NO_x, SO_2, and methanol (MeOH) were detectable, but the inlet and outlet values were too close to derive meaningful emission rates of these gases. Therefore, their results therefore were not reported.

Table 3. Gas analyzers, gases monitored, detection limits, and detection ranges of the Mobile Agricultural Air Quality Laboratory (MAAQL) used to measure emissions from the environmental chamber.

Gas Analyzer	Gases [3]	Detection Limits	Upper Range
Thermo 17i $NO/NO_x/NH_3$ analyzer [1]	NO	1.25 ng/L	24.96 µg/L
	NO_x	1.54 ng/L	30.78 µg/L
	NH_3	0.71 ng/L	14.14 µg/L
Thermo 55C CH_4 analyzer [1]	CH_4	13.31 ng/L	665.56 µg/L
Thermo 450i SO_2/H_2S analyzer [1]	SO_2	3.99 ng/L	26.62 µg/L
	H_2S	2.12 ng/L	14.14 µg/L
Thermo 46i N_2O analyzer [1]	N_2O	0.04 µg/L	36.61 µg/L
Innova 1412 photo-acoustic multi-gas analyzer [2]	CO_2	2.75 µg/L	1.83 g/L
	EtOH	0.15 µg/L	1.91 g/L
	NH_3	0.71 µg/L	0.71 g/L
	MeOH	0.11 µg/L	1.33 g/L
	N_2O	0.05 µg/L	1.83 g/L

[1] Analyzers by Thermo Scientific, Waltham, MA, USA. [2] Analyzer by INNOVA AirTech Instrument, Ballerup, Denmark. [3] NO = nitric oxide; NO_x = oxides of nitrogen; NH_3 = ammonia; CH_4 = methane; SO_2 = sulfur dioxide; H_2S = hydrogen sulfide; CO_2 = carbon dioxide, EtOH = ethanol; MeOH = methanol; N_2O = nitrous oxide.

2.5. Emissions Calculations

Concentration data of the air samples from the environmental chamber over each 15 min period were truncated to remove the first five minutes and last two minutes of the sample to prevent carry over. The following equation was used to calculate emission rate mg/h of gases from the environmental chamber:

$$\text{Emission Rate (mg/h/head)} = \{[(MIX) \times (FL) \times (60)]/MV\} \times (MW) \times (Conv)/\text{Head} \quad (1)$$

where *MIX* is the net concentration (inlet concentration—outlet concentration) in either ppm (parts per million) or ppb (parts per billion), *FL* is the continuous ventilation rate of 51,848 L/min, 60 is the conversion from minute to hour, *MW* is the molecular weight of the gas in grams per mole, *Conv* is a conversion factor of 10^{-3} for concentration in ppm and 10^{-6} for concentration in ppb, and V is the volume of one molar gas at temperature T in liter/mole and is calculated as:

$$V = [(V_s) \times T)]/T_s \quad (2)$$

where V_s is the standard volume 22.4 L at 0 °C, T_s is the standard temperature 0 °C that equals to 273.15 K, T is the air temperature in K equaling to T in °C +273.15.

2.6. Data Analysis

Emission rates from the different manure removal methods were compared to evaluate their respective environmental impacts. All emissions data were analyzed using the lmerTest package in R [13]. The model used to evaluate emissions data is:

$$Y_{ijkl} = \mu + B_i + R_j + F_k + H_l + e_{ijkl} \quad (3)$$

where Y_{ijkl} is the dependent variable, μ is the overall mean, B_i is the block, R_j is the method of removal (scraping versus flushing), F_k is frequency of removal (three times versus six times), H_l is the hour of measurement, and e_{ijkl} is the error term associated with the model. Block was a random effect, with all other variables as fixed effects. The interaction of the main effects of method of removal * frequency of removal, was originally evaluated but removed from the model as this interaction was not significant. The milk data was analyzed using the lmerTest package in R [13]. The model for the milk data is:

$$Y_{ijkl} = \mu + C_i + B_j + D_k + T_l + e_{ijkl} \quad (4)$$

where Y_{ijkl} is the dependent variable, μ is the overall mean, C_i is the cow, B_j is the block, D_k is the date of milking, T_l is the time of milking, and e_{ijkl} is the error term associated with the model. Cow was a random effect, with all other variables as fixed effects. B_i, R_j, F_k, and H_l were categorical variables. Means are presented as least squares means (LSM) and were determined using the lsmeans package in R [14]. Pairwise comparisons of treatment LSM were determined by a Tukey test using the multcompView package in R [15]. Differences were declared significant at $p \leq 0.05$ and showed a trend at $0.05 \leq p \leq 0.10$.

3. Results and Discussion

3.1. Milk Production

Least squares means for milk yield were 42.4, 46.2, 42.7, and 39.9 kg (±6.14 kg; $p = 0.91$) for each of the four groups of cows (blocks) during the duration of the study. Dry matter intake (DMI) for the 11 h period animals were housed in the environmental chamber was similar across treatments with group DMIs of 30.7, 31.1, 34.5, and 34.5 kg (±4.31 kg; $p = 0.25$). A difference in milk yield could lead to differences in feed intake, affecting both manure output and gaseous emissions from manure and enteric sources [16,17].

3.2. Ammonia Emissions

Total NH_3 emissions from scraping were greater than flushing treatments ($p < 0.001$; Table 4). Scraping increased NH_3 emissions by 175 and 152% for S3 and S6, respectively, as compared to the control (F3; Table 4). The most common California industry practice of clearing freestall lanes is by flushing 2 to 3 times a day, which occurs while the cows are in the milking parlor. Scraping treatments left behind a film of manure that coated the concrete freestall lane in the environmental chamber. The urea being excreted in the animal's urine comes in contact with this manure film and is rapidly converted by the urease naturally present in the manure to NH_3 and volatized [18]. In contrast, flushing does not allow for the manure to create a film, which reduces the opportunity for urea to come into contact with urease. The presence of water with the flush treatment may also affect the amount of NH_3 that is volatilized. In the presence of water, NH_3 and ammonium (NH_4^+) exist at an equilibrium in solution that is dependent on pH and temperature [19]. An increase in the concentration of NH_4^+/NH_3 in the manure, an increase of temperature, or a disturbance to the manure, such as wind speed, can increase the volatilization of NH_3 [19–21]. The scraping treatments cause a physical disturbance to the manure and do not dilute the manure, which likely led to the greater NH_3 emission seen in these treatments. Flushing results in a lowering of urea and TAN concentrations in slurry by diluting and removing urine from the floor surface which reduces NH_3 emissions [22]. Kroodsma et al. (1993) found that scraping manure from a concrete stall did not reduce NH_3 emissions while flushing reduced NH_3 by 70% [23]. Urea is usually hydrolyzed within 2 h after urine is excreted on floors, but can continue to volatize for 15 h if left undisturbed [22,24]. Flushing more frequently dilutes the urine and removes it before the majority of the urea is hydrolyzed to NH_3. However, since flushing on commercial dairies occurs primarily when the cows are in the milking parlor, increasing the frequency of flushing would be difficult to implement with current management practices.

Table 4. Least squares means, pooled standard errors (SEM), and *p*-values for the 3 versus 6 times flushing or scraping treatments, respectively, for ammonia, methane, hydrogen sulfide, ethanol, and carbon dioxide emissions ($n = 4$). Emission measurements reported are on a per cow basis in either mg or g/h. A negative reduction potential equates to an increase in emissions.

	Treatment LSM [1]				SEM	*p*-Value		
	F3 [2]	F6	S3	S6		S vs. F [3]	3 vs. 6 [4]	Time
Ammonia								
Emission Rate (mg/h)	622.42 [a]	479.33 [a]	1712.90 [b]	1569.80 [b]	154.70	<0.001	0.12	<0.001
Reduction Potential (%)		23%	−175%	−152%				
Methane								
Emission Rate (g/h)	23.32 [a]	26.29 [b]	26.60 [b]	29.56 [c]	1.69	<0.001	<0.001	0.97
Reduction Potential (%)		−13%	−14%	−27%				
Hydrogen Sulfide								
Emission Rate (mg/h)	2.26	6.16	6.94	7.84	1.56	0.0496	0.29	0.13
Reduction Potential (%)		−173%	−207%	−247%				
Ethanol								
Emission Rate (g/h)	1.65 [ab]	2.17[c]	1.55 [a]	2.07 [bc]	0.13	0.426	<0.001	<0.001
Reduction Potential (%)		−31%	6%	−25%				
Carbon Dioxide								
Emission Rate (g/h)	920.94 [a]	1056.81 [b]	1072.79 [b]	1208.79 [c]	58.42	<0.001	<0.001	0.98
Reduction Potential (%)		−15%	−16%	−31%				

[1] F3 = flush 3 times; F6 = flush 6 times; S3 = scrape 3 times; S6 = scrape 6 times. [2] F3 treatment is industry standard and considered the Control. [3] S = scrape; F = flush. [4] The difference between increasing the frequency of flush or scrape from 3 to 6 times. Means with the same letter ([abc]) are not significantly different ($p > 0.05$).

Ammonia emissions also changed over the 11 h period the cows were in the environmental chamber ($p < 0.001$; Figure 1). Both frequencies of the scraping treatments showed increased NH_3 emissions over the 11 h treatment period showing a compounding effect even after scraping occurred (Figure 1). Comparatively, the flushing treatments show a decrease in NH_3 emissions directly after flushing treatments occurred (Figure 1). The increase in concentration of NH_3 emissions over time for the scraping treatment is consistent with the literature [25,26].

Rotz et al. (2014) measured NH_3 emissions from dairies using both scrape and flushing systems in New York, Wisconsin, and Indiana [27]. Both the model simulation and the measured annual average NH_3 emissions were lower in flush barns compared with scrape barns. Vaddella et al. (2011) compared NH_3 emissions from simulated flushed manure storage with scraped manure storage and controlled for surface-area to volume ratio and found greater NH_3 emissions in the scraped versus flushed manure.

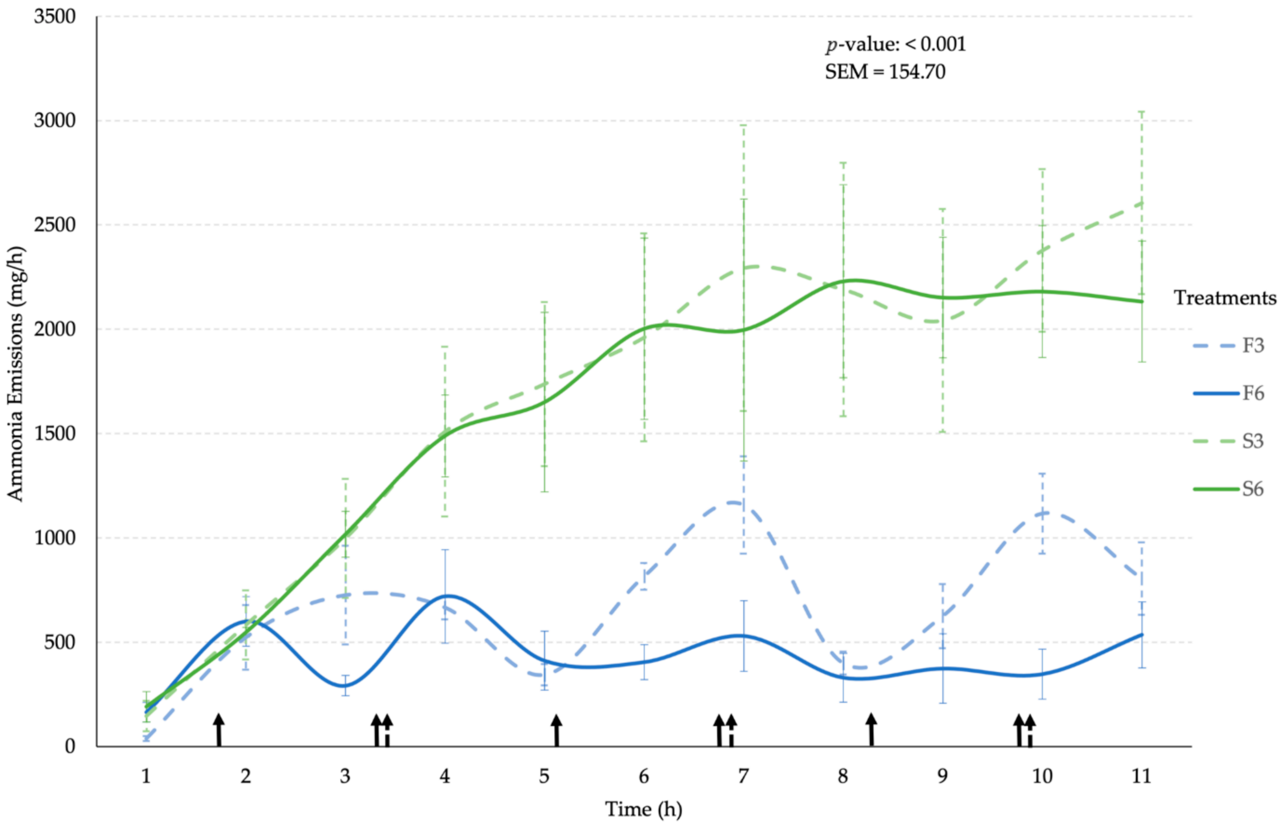

Figure 1. Average ammonia (NH_3) emissions for the four treatments F3 = flush 3 times; S3 = scrape 3 times; F6 = flush 6 times; S6 = scrape 6 times; over time in hours (n = 4). Emission measurements reported are on a per cow basis mg/h. Error bars represent the standard error for each point. The arrows correspond to the frequency of the four treatments applications (number of flushing or scraping events) that occurred in the environmental chamber. Solid arrows correspond to times the F6 and S6 treatments were applied, and dashed arrows correspond to times F3 and S3 treatments were applied.

3.3. Methane Emissions

In the present study, all treatments compared with the Control (F3) had negative reduction potentials (increased emissions) for CH_4 emissions ($p < 0.001$; Table 4). Both F6 and S3 treatments were similar. Surprisingly, the S6 treatment had larger ($p < 0.001$) CH_4 emissions as compared to other treatments. The primary source of CH_4 emissions during the testing period would be from enteric sources, which cannot be differentiated from manure CH_4 emissions inside the environmental chamber.

Sun et al. (2008) conducted a similar study in the same facility as the present study and found that minimal CH_4 emissions were attributed to fresh manure sources [28]. Sun et al. (2008) measured emissions in two phases: first with a cow plus manure, followed by manure only. Methane emissions substantially increased with the addition of the cows to the chamber and subsequently returned to near empty chamber concentrations when the cows were removed [28].

Methane emissions from livestock waste are produced by the decomposition of volatile solids in manure primarily from systems that promote an anaerobic environment, such as lagoons [29]. The production of CH_4 is dependent on methanogens, which thrive in anaerobic environments. Under aerobic conditions such as in an environmental chamber, there is little to no CH_4 production [29].

In the present study, cows were blocked in order to decrease variability in enteric CH_4 emissions. Blocking for milk yield groups cows with a similar dry matter intake, which has a linear relationship with CH_4 emissions [30]. Future research should remove the interference of enteric CH_4 emissions to determine if scraping fresh manure increases CH_4 emissions.

3.4. Hydrogen Sulfide Emissions

In the present study, individual treatments and frequency of treatments showed similar H_2S emissions; however, scraping resulted in higher H_2S emissions ($p < 0.05$) than flushing. Hydrogen sulfide emissions can be particularly dangerous in enclosed animal facilities. Without proper ventilation, a buildup of H_2S can cause mild eye irritation, and in large enough concentrations cause respiratory failure and death [31]. The majority of California dairy freestall barns are open air so health concerns from H_2S exposure are minimal. However, H_2S emissions should be carefully monitored in enclosed animal facilities particularly when the manure is disturbed for cleaning. Mixing or disturbing the surface of manure will lead to an increase in H_2S emissions because H_2S is contained in gas bubbles suspended in the manure, which burst when mixed [25,32,33]. Maasikmets et al. (2015) measured a farm with solid manure storage compared to a farm with liquid manure storage and found the solid manure storage to have a higher concentration of H_2S [34]. The concentration of H_2S was highest in the morning when there was little air movement inside the barns. With less air flow there is less dilution of the air pollutants, allowing for measurements at higher levels. Animal diets also play a key role in the production of H_2S in the manure. Cattle fed a higher concentrate diet, or a diet containing more sulfur substrate, will have manure that produces greater H_2S emissions than cattle fed a high forage diet or low sulfur substrate diet [32].

3.5. Ethanol Emissions

Ethanol emissions were similar for flushing vs scraping; however, flushing and scraping six times versus three times increased EtOH emissions ($p < 0.001$; Table 4). Ethanol emissions changed over the 11 h period in the environmental chamber ($p < 0.001$; Figure 2).

Ethanol is the primary VOC produced on dairies and is a precursor for O_3 formation [35]. Previous studies showed some enteric emissions of ethanol [28]; however, the majority of ethanol emissions comes from the manure. Another possible source of EtOH emission is the total mixed ration (TMR). Chung et al. (2004) quantified non-enteric VOC emissions sources from dairies and showed the highest emissions sources for EtOH to be from silage and silage-based TMR piles [36]. The TMR fed in the present study did not contain silage or other fermented feedstuffs; therefore, VOC emissions from the TMR is expected to be negligible as compared to a silage based TMR. The most common VOCs associated specifically with flush lanes are 2-butanone and toluene, with EtOH being a lesser source [36]. The highest emissions rates from feed occur during the feed out phase, due to greater oxygen exposure [37]. Ethanol is the major contributor of VOCs from animal feed at >70% of the total VOCs [35]. It is likely that the EtOH measured in the chamber during the current study was a combination of enteric processes, TMR, and manure. Further research should determine the effect of agitation on manure EtOH emissions to confirm the findings of the present study, that an increase in frequency of manure removal (i.e., agitation by either flush or scraping) increases EtOH emissions.

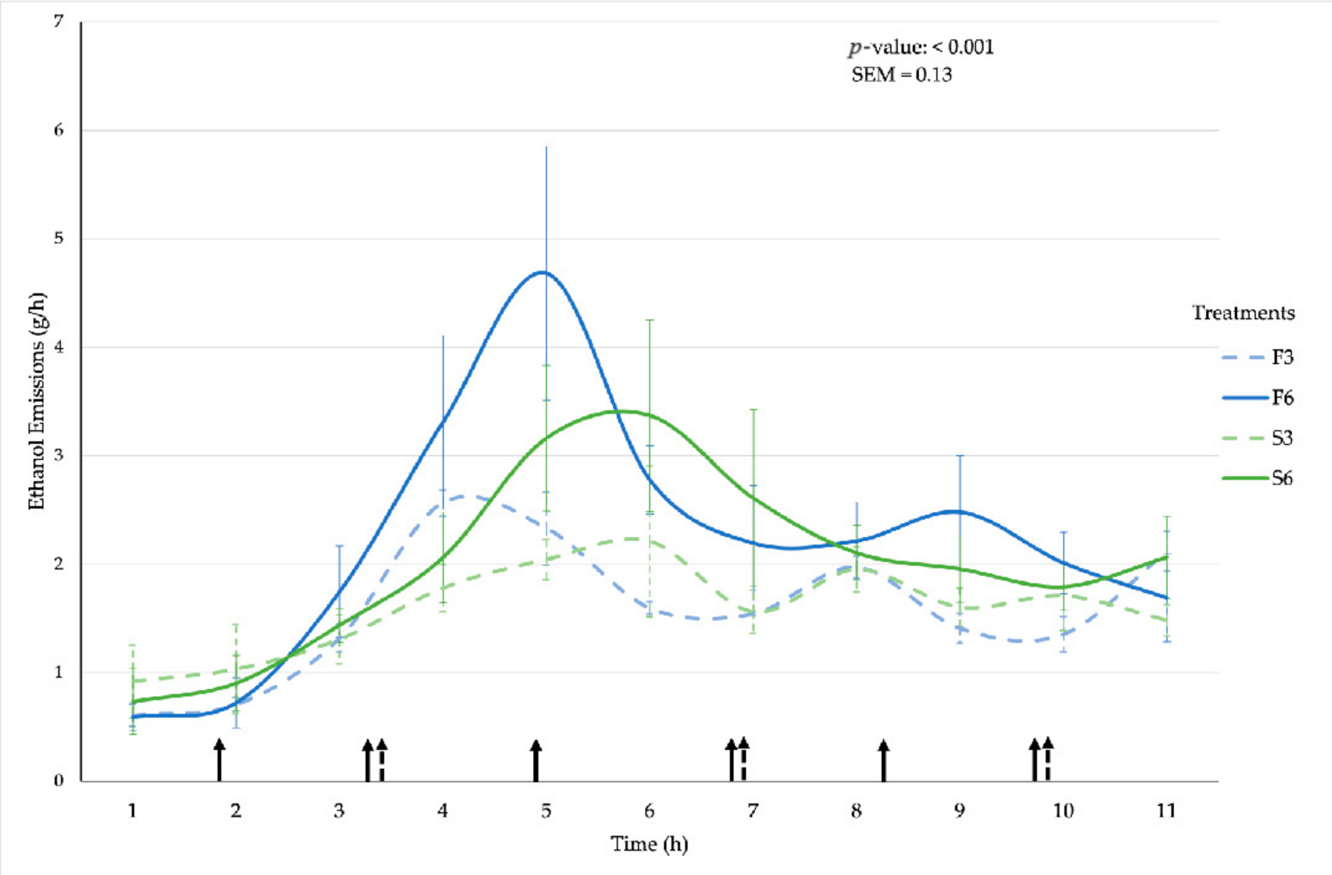

Figure 2. Ethanol (EtOH) emissions for the four treatments F3 = flush 3 times; S3 = scrape 3 times; F6 = flush 6 times; S6 = scrape 6 times; over time in hours ($n = 4$). Emission measurements reported are on a per cow basis g/h. Error bars represent the standard error for each point. The arrows correspond to the frequency of the four treatments applications (number of flushing or scraping events) that occurred in the environmental chamber. Solid arrows correspond to times the F6 and S6 treatments were applied, and dashed arrows correspond to times F3 and S3 treatments were applied.

3.6. Carbon Dioxide Emissions

In the present study, CO_2 increased with scraping and increased frequency of treatments ($p < 0.001$; Table 4). Carbon dioxide emissions can be from animal manure as products of microbial degradation, and from respiratory and enteric emissions [38]. Carbon dioxide from animal manure is a release of carbon sequestered by photosynthesis and is part of the cycling of carbon from the atmosphere to plants to animals and back to the atmosphere over a short period of time. For this reason, the USEPA does not consider CO_2 from animal feeding operations a contributor to the buildup of GHG in the atmosphere [38].

3.7. Relation to Manure Management

The present study has shown that converting from a flush to a scrape manure removal system can result in the unintended consequences of increasing NH_3 emissions. However, manure removal in the housing portion of the dairy is just one portion of the whole manure management system and a lifecycle assessment of the entire manure management train should be conducted.

Covered lagoon anaerobic digesters fit the current manure management system for California dairies better than a higher solids content digester, as this allows farmers to continue using a flush system. However, in either anaerobic digester system, the total ammoniacal nitrogen (TAN) is increased as well as the pH in the digested manure, which results in potentially higher NH_3 volatilization from digested manure [39]. Anaerobic digesters reduce the amount of easily degradable carbon in the manure through fermentation, which reduces CH_4 production from the effluent as well as the potential of N_2O emissions during soil application [40–42]. Montes et al. (2013) determined that N_2O emissions could be reduced by up to 70% from soil applied digested manure compared to fresh manure [43]. Given the changes in composition and gaseous emissions from digested manure, it is imperative to do a whole gaseous emissions balance for the varying manure management strategies to determine the most sustainable option for dairy farmers.

4. Conclusions

Flushing versus scraping manure from dairy freestall lanes was found to be advantageous for reducing both NH_3 and H_2S emissions. The control (F3) treatment showed the lowest CH_4 emissions compared with other treatments, which should be researched further to determine if increased agitation of manure or flushing of manure increases CH_4 emissions. Mitigation of CH_4 from dairy manure sources is vitally important, particularly in California where legislation requires it. For future research, we suggest conducting lifecycle assessments to predict emissions from the entire manure management train, from removal in the barn to storage/treatment, and finally land application. Mitigation strategies such as switching from flush to scrape to reduce CH_4 emissions in dairy housing have the potential to increase other important pollutants such as NH_3. The present study shows that NH_3 emissions are lower in flush vs. scrape systems. To align manure removal with storage, a flush system followed by anaerobic digestion should be considered. This combination would optimize mitigation of two of the most important gases emitted from dairies, CH_4 and NH_3. Potentially, the use of covered lagoon anaerobic digesters would best fit this combination. This is particularly important for areas like the San Joaquin Valley where NH_3 and $PM_{2.5}$ emissions are consistently above the regulatory limits. This research is directly related to the development of a sustainable dairy system, as manure management directly contributes to the environment and economic pillars of sustainability through mitigation of gaseous emission and economic feasibility for dairy producers.

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