Mitigation technologies and practices for reducing CH_4 emissions from animal manure management

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For manure management sector, CH_4 was produced when the organic matter in the manure was anaerobically decomposed by the methanogens. Therefore, CH_4 emission can be happened during the whole manure management chain (MMC), from manure excreted, and the following manure storage and treatment sector, and even in the land application sector when the anaerobically condition provided. Based on the literature review for the CH_4 mitigation options used in the major animal categories, including pig, dairy, beef cattle and poultry (Table 1-4), the mitigation technologies, practices and the possible integrated mitigation technologies were summarized, and the best technology recommended for each stage was also summarized (Table 5). Meanwhile, the possible effects of the technologies on N_2O and NH_3 emissions were also evaluated simultaneously.

1 CH_4 mitigation technologies used in each stage of the manure management chain

1.1 In house sector

The CH_4 mitigation options used in this sector including change manure characteristics by manipulating animal diet, changing to a better manure cleaning system, and reducing the exhausted CH_4 emission to the ambient environment by using biofilter.

1.1.1 Manipulating animal diet

Wu-Haan et al. (2007) reported that the emission reduction diet (RE diet) containing 6.9% of a $CaSO_4$-zeolite mixture and slightly reduced crude protein (CP) can reduce the CH_4 emission by 10.3-36% in hen facility. Kim et al. (2004) found that an acidogenic Ca and P source ($CaSO_4$-H_3PO_4) in swine diets could decrease the urinary pH and reduce CH_4 emission by 14% from swine facilities. $CaSO_4$ was added to the diet as an acidifying agent, which caused the decrease of pH. A reduction in manure pH or perhaps reduced manure VFA could explain the reduced CH_4 emission based on the RE diet (Wu-Haan et al., 2007). However, another acidifying diet by adding $CaCl_2$ caused the in-house CH_4 emission increased by 73% (Eriksen et al., 2014). Meanwhile, the reduced manure pH caused by the acidifier diet led to the NH_3 emission being reduced by 27-46% (Wu-Haan et al., 2007; Eriksen et al., 2014).

On the other hand, Wiedemann et al. (2016) reported that the CH_4 emission can be reduced by 26% by using low CP diet in layer production. However, Menezes et al. (2016) found there is no significant influence on manure CH_4 emissions by using LCP diet in beef cattle production.

1.1.2 Optimization for manure cleaning system

Increasing manure cleaning frequency can reduce the manure retention time in animal house, and therefore may reduce the CH_4 emission. Ulens et al. (2014) found the in-house CH_4 emission was reduced by 39% by increasing the manure cleaning frequency. Wang et al. (2017) compared the in-house CH_4 emission factor of four typical pig manure collection method based on meta-analysis. The results show that different in-house manure collection methods have a significant impact on gas emissions, especially for CH_4 and N_2O. The CH_4 EF is largest for the deep-pit mode (median value of 64.37 kg CH_4 AU^{-1} yr^{-1}), because manure in deep-pits with long storage periods is conducive to generation of CH_4 due to anaerobic conditions. The pull-plug mode with manure regularly removed has the next highest CH_4 EF of 47.09 kg CH_4 AU^{-1} $year^{-1}$. In comparison, CH_4 emissions for separation mode are much lower with an EF of 10.93 kg CH_4 AU^{-1} yr^{-1}. The bedding mode has comparatively the lowest CH_4 EF (10.63 kg CH_4 $^{-1}AU^{-1}$ yr^{-1}) but the highest N_2O EF (4.70 kg N_2O AU^{-1} yr^{-1}) due to the nitrification and denitrification processes, which are facilitated by the co-existence of aerobic and anaerobic areas in the continuously accumulating manure on the animal house floor. For NH_3 emissions, the bedding mode shows the lowest median value of 8.05 kg NH_3 AU^{-1} yr^{-1}; whereas for deep-pit, pull-plug and separation modes, the median NH_3 EFs are higher, in the range of 11.99-14.98 kg NH_3 AU^{-1} yr^{-1}. Therefore, changing manure cleaning system can achieve high CH_4 mitigation effect; with the CH_4 EF being reduced by 83% when the in-house manure collection method was changed from deep-pit method to solid-liquid separation method. Meanwhile, the difference of floor system (solid floor without urine drainage vs. slatted concrete floor) used in dairy house seemed have no significant influence on CH_4 emission (Pereira et al., 2011). However, the slatted floor can reduce NH_3 emission by 16-29% when compared with the solid floor. The reduced surface area of slatted floor caused the lower NH_3 emission. However, as the N_2O emission was quite low being lower than 0.1% of the total N deposited on the floors, it's hard to compare the N_2O emission from the two systems (Pereira et al., 2011).

1.1.3 Litter additives

Many different kind of litter additives were proved to be quite efficient in reducing the NH_3 emissions in animal house, including alum (Eugene et al., 2015), Na bisulfate (PLT) (Shah et al., 2014), zeolite (Schneider et al., 2016). The mechanisms including reducing manure pH or adsorbing the polluted gases. However, Eugene et al. (2015) reported the concentrations and emissions of nitrous oxide (N_2O) and methane (CH_4) from the alum-treated house were not significantly different from the untreated house.

1.1.4 biofilter used for exhausted air

Biofilters are widely used to reduce NH_3, H_2S, and to reduce CH_4 emissions of the exhausted air from the animal house (Gerber et al., 2013). The commonly used substrate materials for biofilters include manure compost, peat, wood chips, as well as some inorganic substrate materials added with microbial agents. Janni et al. (2014) found that the use of biofilter to treat the discharged gas outside the deep pit can reduce CH_4 emissions by 8-35%. Akdeniz et al. (2012) found that the CH_4 emission from the exhaust air of the pig house can be reduced by 22-28%. Meanwhile, methane removal up to 85% could be achieved in the experimental biofilter for treating air from the headspace of a covered 6 m^3 liquid manure storage (Melse and van der Werf, 2005). A large number of methane oxidizing bacteria are generally accumulated on biofilter, so CH_4 in the gas is oxidized and converted into CO_2 when passing through the biofilter

(Melse and Ogink, 2005). However, a large amount of NH_3 also existed in the exhaust air. The biofilter can reduces NH_3 emissions effectively through nitrification and denitrification, and the N element in NH_3 would be partly converted into N_2O and N_2. Therefore, most studies have also found that the use of biofilters can increase N_2O emissions by 12-81% (Akdeniz et al., 2012; Janni et al., 2014). Melse et al. (2012) demonstrated that for a full-scale packed-bed biotrickling filter, 5% of the removed NH_3-N was converted into N_2O-N in the biofilter and emitted as N_2O

1.2 Outdoor slurry storage

For CH_4 mitigation from slurry storage, cover, acidification and anaerobic digestion are the technologies which are widely used in practice or studied. Meanwhile, other possible measures include cooling and solid-liquid separation.

1.2.1 Covers

Different types of covers can be used to reduce the gas emissions from animal slurry storage. However, the difference in the cover material, cover thickness, the climate condition and the using time may all influence the CH_4 mitigation effect. It is generally believed that the use of plastic film has a constant effect on CH_4 (Guarino et al., 2006), as plastic covering with secure sealing characteristics could help to avoid gas emissions. Straw is usually rich and cheap, and was widely studied to evaluate its effect on gas mitigation. Hansen et al. (2009) reported straw can reduce the CH_4 emission by 26-50%, and Clemens et al. (2006) also reported the CH_4 mitigation efficiency can reach 12-27% for dairy slurry storage with straw cover. However, some studies also reported the straw cover increased the CH_4 emission by 3-76% (Berg et al., 2006; Guarino et al., 2006; Petersen et al., 2013; Amon et al., 2006; Clemens et al., 2006). It's reported that the decomposition of straw, if used for a prolonged period, may serve as an additional carbon source for methanogens, thus increasing CH_4 emission (Amon et al., 2006). Different kind of granules can also serve as cover, and the granule covers can reduce CH_4 emission by 9-14% (Berg et al., 2006; Guarino et al., 2006; Li, 2008). Oil can also be cover, and the floating oil can reduce CH_4 emission by 10-13% (Guarino et al., 2006). Regardless of the varied materials, all the covers are efficient in NH_3 mitigation, with the mitigation efficiency (ME) being usually higher than 50%. However, the use of straw cover and granule cover may usually increase N_2O emissions, due to nitrification and denitrification processes occurring within the cover (Hansen et al., 2009; Berg et al., 2006). Although the cost of plastic film is higher than that of straw, its service life can be 20-25 times that of straw (Hörnig et al., 1999).

1.2.2 Slurry acidification

Acidification of animal slurry is a widely recognized NH_3 reduction measure (Kai, 2008). Meanwhile, slurry acidification has also been shown to be effective in reducing CH_4 emissions. Shin et al. (2019) adjusted the slurry pH at 5.0-7.0 using H_2SO_4 solution, and found the CH_4 emission can be reduced by 51-97%. Misselbrook et al. (2016) reported that compared with non-acidification conditions, acidifying dairy slurry to pH 5.5 can reduce CH_4 emission by 63-90%. Wang et al. (2014a) reported that comparing with control, adjustment of initial pH of digested pig slurry to 5.5 significantly reduced CH_4 emissions by 80.8% and NH_3 emissions by 40.2%, but increased H_2S emissions by 11,324%; acidification with pH adjusted to 6.5 reduced CH_4 emissions by 31.2%, but did not affect NH_3 and H_2S emissions significantly. Besides the commonly used H_2SO_4, other types of acid were also tried to reduce the operation risk, including latic acid, citric acid (Im et al., 2021), $FeCl_3$, and even some organic material which can cause self-acidification in the slurry, such as spent brewers' grain, sugarbeet (Kavanagh et al., 2021; Bastami et al., 2016). They are all proven to be effective in reducing CH_4 emission, with the reported ME being in the range of 6-99% (Im et al., 2021; Kavanagh et al., 2021; Bastami et al., 2016). After the slurry is acidified to pH 5.5-6.0, the activity of internal methanogens is greatly reduced, and thus the methane mitigation effect is obtained (Shin et al., 2019). Ottosen et al. (2009) found that by adjusting the slurry pH to 5.5, the oxygen consumption rate and methanogenic activity in pig slurry decreased by 98%. However, the effect of acidification on N_2O is not clear. Berg et al. (2006) reported that the combination of acidifying slurry to pH 6.0 and perlite coverage can reduce NH_3, CH_4 and N_2O by 92%, 87% and 100%, respectively. In the same study, Berg et al. (2006) proved that the use of coverage alone would increase N_2O emission by 114%-152%, so it can be inferred that the addition of lactic acid is the main factor causing N_2O emission reduction.

1.2.3 Slurry Cooling

Since methanogens are extremely sensitive to temperature, cooling is an effective mean to reduce CH_4 emissions (Umetsu et al., 2005; Petersen et al., 2013). Wang et al.

(2016) compared the emission characteristics of CH_4, N_2O and NH_3 during slurry storage at 5-25℃, and found that CH_4 emission is very small when the temperature is lower than 15°C (Wang et al., 2016). Lowering slurry storage temperature from 25°C to 20°C can reduce CH_4 emissions by 15%, while further reducing the temperature to lower than 15°C can reduce CH_4 emissions by 84-93% (Wang et al., 2016). Misselbrook et al. (2016) compared the CH_4 emission from pig and dairy slurry under cool, temperate and warm conditions, and found the CH_4 emission under cool condition was 98-99% lower than that under warm condition. In low temperature regions, frequent removal of manure from the house to the outside is a low-cost CH_4 mitigation option (Sommer et al., 2013; Petersen et al., 2013; Groenestein et al., 2012). As there are abundant methanogens existed in the fresh biogas slurry, the rapid cooling will reduce CH_4 emission as the methanogens usually produce CH_4 under mesophilic condition. Therefore, Sommer et al. (2000) suggested that the fresh biogas slurry should be cooled before it was stored in the storage tank to reduce CH_4 emissions. Temperature is one of the most important factors in determining NH_3 emission. Cooling slurry from 25 ^{o}C to 5 ^{o}C can reduce NH_3 emission by 60% (Dinuccio et al., 2008). N_2O comes from nitrification and denitrification, and the activity of nitrifier and denitrifier was also affected by temperature. It's found that temperature higher than 25°C may stimulate N_2O emission (Wang et al., 2016). Therefore, cooling can also reduce N_2O emissions effectively.

1.2.4 Anaerobic fermentation

Biogas recovery and utilization exhibited a high GHG mitigation potential. The substitution of the fossil fuel with the generated CH_4 is accounted into the GHG mitigation effect. For the CH_4 emission during the anaerobic fermentation process, approximately 10% of the CH_4 generated from biogas digesters may subsequently leak to the air according to 2006 IPCC guideline. Meanwhile, CH_4 loss from digestate storage is not negligible, and 5-15% additional biogas yield from digestate storage has been reported. All of these emissions should be taken into account when assessing the mitigation effect of biogas digesters. Unfortunately, there is no literature reporting a direct comparison of biogas digester *vs.* the baseline scenario. Therefore, the difference between the CH_4 emission from the biogas slurry storage and the raw slurry storage was regarded as the CH_4 mitigation effect in this study. As most of the organic matter has been decomposed during the anaerobic digestion process, there is always low organic matter being reserved in the biogas slurry. Therefore, the CH_4 emission from the biogas slurry was 67-99% lower than the raw slurry (Wang et al., 2014b; Amon et al., 2006; Maldaner et al., 2018; VanderZaag et al., 2018), although there is also one study reporting that the CH_4 emission may be increased by 234% when compared with the raw slurry (Rodhe et al., 2015). The NH_3 emission in biogas slurry was 41-45% lower than raw slurry (Wang et al., 2014; Amon et al., 2006). However, the biogas slurry usually emitted much higher N_2O than the raw slurry, being 76-362% (Wang et al., 2014b; Amon et al., 2006), mainly caused by the decreased COD/N in the digested slurry (Wang et al., 2014b).

1.2.5 Other mitigation options

It's reported that the CH_4 emission from the aerated slurry can be 57-87% lower than the control (Amon et al., 2006; Loyon et al., 2007). However the aeration procedure may increase N_2O emission and NH_3 emission by 144% and 409%, respectively (Amon et al., 2006). Mechanical separation of slurry into its solid and liquid components is widely used to ease the transport of nutrients surplus outside livestock dense areas towards livestock-free plantations (Maffia et al., 2020). The solid-liquid separation caused the CH_4 emission from the liquid part being 42-81% lower than the raw slurry (Amon et al. 2006; VanderZaag et al., 2018). However, the NH_3 emission from the liquid part was much higher than the raw slurry (Amon et al. 2006).

1.3 Manure compost

For manure compost, the possible CH_4 mitigation measures include compost additive, compost biofilter. Meanwhile, cover was also tried to reduce the gas emissions from the compost process.

1.3.1 Compost additive

The compost additives were usually used for reducing NH_3 emission hence improving the retention of N in the final compost product. The commonly used additives include some inorganic additives, such as modified red mud, superphosphate, modified forsterite, and also include biochar, microbial additives, etc. Hao et al. (2005) reported that adding phosphogypsum in beef cattle manure composting with an amount of 10-30% of the dry weight can reduce CH_4 emissions from 15.36 kg C/Mg to 0.44-2.83 kg C/Mg, and higher mitigation was achieved with higher additive amount. Phosphogypsum brings in SO_4^{2-} ions, and SO_4^{2-} ions are toxic to methanogens, leading to a reduction in methane production (Hao et al., 2005; Shin et al., 2019). Different from CH_4 emission, adding phosphogypsum to cattle manure compost may increase N_2O emissions by 78-156% (Hao et al., 2005). As phosphogypsum addition can significantly reduce NH_3 emissions, it may lead to more N being retained in the compost pile, providing more N element for N_2O generation from nitrification and denitrification. Yang et al. (2015) reported that the superphosphate addition in compost can reduce CH_4 emission by 32-84%. However, Luo et al. (2012) found that adding superphosphate to pig manure compost may increase CH_4 by 4-15%. Biochar addition can reduce CH_4 emission from poultry manure compost process by 78-84% (Chowdhury et al., 2014; Agyarko-Mintah et al., 2017). Some studies reported a lower CH_4 mitigation effect with biochar addition, being 6-26% (Chen et al., 2017; Chen 2016). Biochar was usually deemed with relatively stable properties and it is difficult to be degraded by microorganisms as a C source; in addition, the addition of biochar may increase the pores of the compost pile, leading to a better aerobic condition, thus contributing to reducing CH_4 emissions (Agyarko-Mintah et al., 2017). However, if the biochar is added as powder, it may cause the increase of CH_4 emission by 57% because of the decreased aerobic condition (He et al., 2018). The use of bulking agent such as straw can also help reduce CH_4 emission, being in the range of 45-74% as these materials help reduce the density but improve the porousness of the pile; meanwhile, the N_2O can be reduced by 11-64% (Yamulki et al., 2006; Maeda et al., 2013).

1.3.2 Compost biofilter

Biofilter can also be used to treat the exhaust air from composting process. Zhou (2017) found the biofilter for treating the exhaust air from pig manure compost can reduce CH_4 emission by 85%. It can also reduce NH_3 emission efficiently, with the ME being in the range of 81-100% (Park 2002; Xue et al., 2010).

1.3.3 Compost cover

With the plastic foil cover, the CH_4 emission from compost was increased by 32-57% because of the worse aerobic condition (Jiang et al., 2011, 2013). However, cover can reduce the N_2O and NH_3 emission, being in the range of 10-39% and 3-35%, respectively (Jiang et al., 2011, 2013).

1.4 Manure stockpile

The effect of cover on CH_4 emission from manure stockpile was not consistent. Hansen et al. (2006) reported that the Polyethylene cover can reduce CH_4 emission from pig manure stockpile by 88%. Naylor et al. (2016) reported the impermeable cover caused CH_4 emission increasing by 6300% from poultry manure stockpile. For straw cover, it may increase CH_4 emission by 6-44% (Zhu et al., 2014, 2017). Cover showed a consistent mitigation effect on NH_3 emission. The impermeable cover can help reduce N_2O emission. However, the straw cover may sometimes increase the N_2O emission (Zhu et al., 2014). The carbon input sourcing from the straw and sawdust stimulated the nitrification and denitrification process in the pile, and may trigger the increased N_2O emissions.

1.5 Land application

For CH_4 mitigation from rice paddy field, it's widely found that replacing chemical fertilization with manure application usually increases the CH_4 emission (Pandey et al., 2014; Yang et al., 2015). The CH_4 emission from the cropland was usually low as the cropland was usually seen as carbon sink. The mitigation options used in cropland usually aimed at lowering NH_3 and N_2O emission, thus lowering the odor emission, GHG emission and enhancing the N retention in the field. Changing slurry broadcast to slurry injection can reduce NH_3 emission by 78%, and the CH_4 emission was also reduced by 39% (Fangueiro et al., 2015). The NH_3 emission can be reduced by 97% if the applied slurry was being pre-acidified, however, the CH_4 emission may be increased by 18% (Fangueiro et al., 2015). Nitrification inhibitor (NI) additive was efficient in reducing the N_2O emission, with the ME being 47-88% (Cahalan 2015; Tao et al., 2008; Minet et al., 2015). Meanwhile, Minet et al. (2015) reported the CH_4 emission may also be reduced by 42% by using NI additive. The effect of substituting the raw slurry with biogas slurry on gas emissions was not consistent (Clemens et al., 2006; Amon et al., 2006).

1.6 Selection of the most recommended technology for each stage

Based on the literature review, the recommended CH_4 mitigation options in each stage were listed in Table 5. For the in-house stage, increasing the manure removal frequency is quite recommended in reducing CH_4 emission, with the mitigation efficiency being in the range of 27-39%. However, it's effect on N_2O and NH_3 emission was not sure. Biofilter is useful in reducing the CH_4 emission from the exhaust air, with the CH_4 ME being 8-85%. Meanwhile, the NH_3 can also be mitigated simultaneously with the ME being 53-90%. However, the N_2O may be increased because of the nitrification and denitrification mechanism in reducing NH_3 emission.

Acidification is quite recommended for reducing CH_4 emission from slurry storage, with the CH_4 ME being 31-99%, and the NH_3 can also be reduced by 49-84% by using this technology. However, its effect on N_2O emission was not sure.

For manure compost, the biofilter can also be used to treat the exhaust air of the compost pile, with CH_4 emission being reduced by 85%. The NH_3 emission can be reduced by 81-100%, and the N_2O emission may be increased. Meanwhile, biochar was supposed to be an effective additive for reducing the CH_4 emission from compost process, with the ME being 6-88%. The NH_3 can also be reduced by 9-43% by adding biochar. In addition, biochar addition may also decrease the N_2O emission by 11-75%.

For manure stockpile, no mitigation option was proven to be usually efficient in CH_4 mitigation. But the used cover can usually reduce NH_3 emission.

For land-application, crop-land was usually seen as CH_4 sink while rice paddy field may be an important source of CH_4 emission. However, there is quite little literature being available for studying the CH_4 mitigation options. Therefore, no mitigation option for CH_4 mitigation was recommended in this stage.

Table 1 Effects of different management options on CH_4 emissions together with N_2O and NH_3 emission from pig manure management

Stage	Mitigation option		CH_4	N_2O	NH_3	Reference
Housing	diet additive	with $CaSO_4$-H_3PO_4	(-14%)			Kim et al., 2004
		with $CaCl_2$	73%		(-37%)	Eriksen et al., 2014
	biofilter		(-80%)~(-85%)			Melse and van der Werf, 2005
			(-8%)~(-35%)	12% ~ 81%	(-53%)~(-86%)	Janni et al., 2014
			(-22%)~(-28%)	12%~29%	(-61%)~(-86%)	Akdeniz et al., 2012
			(-31%)	(-16%)	(-90%)	Hood et al., 2015
			(-18%)			Girard et al., 2011
	Increase manure cleaning frequency		(-39%)			Ulens et al., 2014
			(-27%)		25%	Wang et al., 2017
Slurry storage	straw cover		49%	468%	(-75%)	Berg et al., 2006
			7~60%		(-14%)~(-84%)	Guarino et al., 2006
			(-8%)~(-28%)		(-1%)~(-86%)	Guarino et al., 2006
			(-26%)~(-50%)	1438~10692%		Hansen et al., 2009
			(-9%)~(-29%)	39600%	(-50%)~(-89%)	Petersen et al., 2013
			76%		(-64%)	Petersen et al., 2013
	oil cover		(-10%)~(-13%)		(-80%)~(-100%)	Guarino et al., 2006
					(-93%)	Portejoie et al., 2003
					(-50%)~(-85%)	Hornig et al., 1999
	granule cover	Perlite cover	(-14%)	280%	(-90%)	Berg et al., 2006
		leca cover	0%	262%	(-83%)	Berg et al., 2006
		Expanded clay cover	(-9%)~(-17%)		(-17%)~(-75%)	Guarino et al., 2006
		Clay cover	(-14%)			Li, 2008
	cooling		(-23%)~(-46%)			Groenestein et al., 2012
			(-61%)	no effect	(-60%)	Dinuccio et al., 2008

Stage	Mitigation option		CH_4	N_2O	NH_3	Reference
			(-15%)~(-93%)	(-81%)~(-91%)	(-4%)~(-84%)	Wang et al., 2016
	acidification	H_2SO_4	(-31%)~(-81%)		(-40%)	Wang et al., 2014a
		H_2SO_4	(-44%)~(-94%)		(-49%)~(-84%)	Petersen et al., 2014
		H_2SO_4	(-51%)~(-97%)			Shin et al., 2019
		citric acid	(-85%)~(-99%)			Im et al., 2021
	aeration		(-87%)		(-96%)	Loyon et al., 2007
	anaerobic digestion		-99%	362%	(-45%)	Wang et al., 2014b
compost	additive	superphosphate	(-22%)~(-63%)	(-21%)~(-26%)	(-23%)~(-42%)	Luo et al., 2012
		superphosphate	4%~15%	(-14%)~(-32%)	(-56%)~(-64%)	Luo et al., 2012
		biochar (powder)	57%			He et al., 2018
		biochar (granular)	(-22%)			He et al., 2018
	cover	Plastic foil	32%~46%	(-10%)~(-39%)	(-3%)~(-35%)	Jiang et al., 2013
		Plastic foil	44%~57%	(-25%)~(19%)	(-10%)~(-20%)	Jiang et al., 2011
	biofilter		(-85%)		(-81%)~(-99%)	Zhou, 2017
solid stockpile	cover	Polyethylene cover	(-88%)	(-99%)	(-12%)	Hansen et al., 2006

Table 2 Effects of different management options on CH_4 emissions together with N_2O and NH_3 emission from dairy manure management

Stage	Mitigation option		CH_4	N_2O	NH_3	Reference
Housing	slatted vs solid		0%	(-9%)	(-16%)	Pereira et al., 2011
			4%	(-49%)	(-24%)	Pereira et al., 2011
			(-10%)	(-38%)	(-29%)	Pereira et al., 2011
slurry storage	cooling	to lower than 15 oC	(-43%)~(-100%)			Clemens et al., 2006
		to lower than 15 oC	(-98%)~(-99%)		(-48%)~(-68%)	Misselbrook et al., 2016
	cover	wood cover	(-14%)~(-16%)	(20%)~(-13%)	(-28%)~(-46%)	Clemens et al., 2006
		straw cover	3%	0-5%	(-20%)~(-44%)	Clemens et al., 2006

Stage	Mitigation option		CH_4	N_2O	NH_3	Reference
		straw cover	21%	109%	24%	Amon et al., 2006
		straw+wood cover	(-12%)~(-27%)	(1%)~(-15%)	(-21%)~(-65%)	Clemens et al., 2006
		calcium carbonate + hydrophobic silia cover	102%-117%			Sakamoto et al., 2008
		superphosphate + hydropholic silia cover	(-65%)~(-45%)			Sakamoto et al., 2008
	Biofiltration		(-90%)~(-99%)		(-69%)	Pratt et al., 2012
	Acidification	H_2SO_4	(-63%)~(-90%)		(-56%)~(-99%)	Misselbrook et al., 2016
		H_2SO_4	1.0%	4%	(-69%)	Owusu-Twum et al.2017
		H_2SO_4	(-69%)~(-84%)			Habtewold et al., 2018
		H_2SO_4	(-68%)		(-62%)	Sommer et al., 2017
		H_2SO_4	(-67%)~(-87%)			Petersen et al., 2012
		H_2SO_4	(-87%)~(-89%)		(-41%)~(-53%)	Sokolov et al., 2020
		Brewing sugar	(-87%)~(-99%)			Bastami et al., 2016
		organic material	(-15%)~(-70%)		(-38%)~(-67%)	Kavanagh et al., 2021
		$FeCl_3$	(-6%)~(-65%)		(-20%)~(-68%)	Kavanagh et al., 2021
	Aerated		(-57%)	144%	409%	Amon et al., 2006
	Solid-liquid separated		(-42%)	10%	698%	Amon et al., 2006
			(-81%)			VanderZaag et al., 2018
	Anaerobic digestion	biogas slurry vs raw slurry	(-67%)	76%	(-41%)	Amon et al., 2006
		biogas slurry vs raw slurry	234%	occurred		Rodhe et al., 2015
		biogas slurry vs raw slurry	(-85%)			Maldaner et al., 2018
		biogas slurry vs raw slurry	(-59%)			VanderZaag et al., 2018
Compost	Mixed with old slurry		129%	(-11%)	(-69%)	Wood et al., 2014
	additive	straw	(-50%)~(-45%)	(-11%)~(-42%)		Yamulki et al., 2006
	additive	Bulking agent	(-74%)	(-64%)	127%	Maeda et al., 2013
Land Application	Acidification		18%	(-3%)	(-97%)	Fangueiro et al., 2015

Stage	Mitigation option		CH_4	N_2O	NH_3	Reference
					(-96%)	Owusu-Twum et al.2017
	NI additive		(-42%)	(-88%)		Minet et al., 2015
	pre-digested	digested vs raw	(-41%)	5%	12%	Clemens et al., 2006
		digested vs raw	54%	(-29%)	18%	Amon et al., 2006
	pre-seperated	separated vs raw	1415%	68%	(-59%)	Amon et al., 2006
					(-49%)	Owusu-Twum et al.2017
	Injection		(-39%)	(-13%)	(-78%)	Fangueiro et al., 2015

Table 3 Effects of different management options on CH_4 emissions together with N_2O and NH_3 emission from beef cattle manure management

Stage	Mitigation option		CH_4	N_2O	NH_3	Reference
Feed	low CP		no significant influence			Menezes et al., 2016
Slurry	additive	effective microorganisms	(-15%)~(27%)			Bastami et al., 2016
		sugar	(-89%)~(-99%)			Bastami et al., 2016
		sugar + effective microorganisms	(-85%)~(-99%)			Bastami et al., 2016
Compost	additive	phosphogypsum	(-82%)~(-97%)	78%~157%		Hao et al., 2005
	biofilter				(-81%)~(-100%)	Park et al., 2002
	biofilter				(-95%)	Xue et al., 2010
Stockpile	cover	straw cover	5.7~21%	24.9~30.7%		Zhu et al., 2014
		sawdust cover	17.6~43.8%	(-20%)~(25%)	(-15%)~(-58%)	Zhu et al., 2017
	cooling		(-94%)			Mathot et al., 2012
	straw addition		(-45%)~(-51%)			Yamulki et al., 2006
Land application	additive	nitrification inhibitor	no significant influence	(-47%)~(-71%)		Cahalan et al., 2015
		nitrification inhibitor		(-73%)~(-79%)	5%-100%	Tao et al., 2008

Table 4 Effects of different management options on CH_4 emissions together with N_2O and NH_3 emission from layer manure management

Stage	Mitigation option		CH_4	N_2O	NH_3	Reference
In house	LCP diet		(-26%)	(-7%)	(-27%)	Wiedemann et al., 2016
	diet additive	emission reduction diet	(-10%)		(-27%)	Wu-Haan et al., 2007
		emission reduction diet	(-36%)		(-45%)	
		emission reduction diet	(-17%)		(-46%)	
	Litter additive	alum	7%		(-52%)	Eugene et al., 2015
		alum	28%		(-51%)	
		alum	17%		(-40%)	
Compost	additive	biochar	(-11%)~(-26%)		(-9%)~(-25%)	Chen et al., 2017
		biochar	(-78%)~(-84%)	(-11%)~(-16%)	(-35%)~(-43%)	Chowdhury et al., 2014
		biochar	(-78%)~(-83%)	(-68%)~(-75%)		Agyarko-Mintah et al., 2017
		biochar	(-6%)~(-22%)		(-21%)~(-33%)	Chen 2016
		superphosphate	(-32%)~(-84%)	(-2%)~(-36%)	(-14%)~(-27%)	Yang et al., (2015)
Stockpile	cover	impermeable cover	6300%	(-100%)	(-88%)	Naylor et al., 2016

Table 5 Best options for reducing CH_4 emission from each stage of animal manure management

Stage	Mitigation option	CH_4	N_2O	NH_3
In-house	frequent removal	(-27%)~(-39%)	not sure	not sure
Exhaust air	biofilter	(-8%)~(-85%)	increase	(-53%)~(-90%)
Slurry	Acidification	(-31%)~(-99%)	not sure	(-49%)~(-84%)
compost	biofilter	(-85%)	increase	(-81%)~(-100%)
	biochar additive	(-6%)~(-88%)	(-11%)~(-75%)	(-9%)~(-43%)
stockpile	cover	not sure	not sure	(-15%)~(-88%)

2 Integration of the technologies

Integrated technology can be used to achieve a better gas mitigation effect. For slurry storage, cooling and acidification can be combined to reach a better CH_4 mitigation effect. Im et al. (2020) reported that to achieve 70% CH_4 reduction, 1.6 kg H_2SO_4/ton pig slurry was needed in pig slurry acidification, which was decreased to 0.5 kg H_2SO_4/ton pig slurry by decreasing temperature from 35 °C to 25 °C. The CH_4 reduction efficiency of storage-temperature decrease was more effective in the acidified PS with low strength. Meanwhile, acidification can also be combined with the coverage. Berg et al. (2006) reported that the combination of acidifying slurry to pH 6.0 and perlite coverage can reduce CH_4, N_2O and NH_3 by 87%, 100% and 92%, respectively. Wang et al. (2021) also reported that for the combination of acidification and coverage technology by using H_2SO_4-modified expanded vermiculite on slurry surface, the CH_4 and NH_3 emissions can be reduced by 52% and 87%, respectively. The MEs of the combined technology were comparable with those achieved by acidifying slurry to pH 6.0, with the CH_4 and NH_3 being reduced by 50% and 90%.

For land-application, Fangueiro et al. (2018) reported that compared with slurry injection, band application of acidified slurry without soil incorporation reduced the N_2O and CH_4 emissions by 65% and 40%, respectively. The lower CH_4 production after amendment with acidified slurry could be related to the lower soil pH that might have inhibited methanogenesis (Fangueiro et al., 2015).

For the whole MMC, Sajeev et al. (2017) reported that a shift from single-stage emission abatement options towards a whole-chain perspective is vital in reducing overall emissions. It was recommended that the best integrated CH_4 mitigation package used in animal MMC included frequent manure removal during housing stage, using acidification for manure treatment, and using covers during manure storage stage. No option was recommended for the land-application stage because of the almost nil CH_4 emission during this stage.

After a pre-screening of the best mitigation option in each stage by using meta-analysis, Wang et al. (2017) recommended the combined mitigation strategies used for reducing CH_4 emission from the whole pig MMC, including the in-house stage, manure storage and treatment stage. As usually no CH_4 emission occurred in the land-application stage, the mitigation package was targeted at the first two stages.

For the two liquid manure management chain, including deep-pit pig MMC and pull-plug pig MMC, the combination of low-CP diet, biofilter for treating the house exhaust air, and the slurry acidification can reduce 59-63% of the CH_4 emission from the whole MMC. Although N_2O emission was increased by using biofilter, the total GHG was still reduced by 47-51% as CH_4 was the major GHG contributor in liquid manure management system. Meanwhile, the NH_3 emission of the chain can also be reduced by 38%-40% (Wang et al., 2017).

For bedding system, the combined use of LCP diet, biofilter for treating the house exhaust air and compost additive can reduce the whole chain CH_4 emission by 23%. However, the total GHG can only be reduced by 10%, as the use of biofilter may increase N_2O emission. Meanwhile, the whole chain NH_3 can be reduced by 41% with this mitigation package (Wang et al., 2017).

For solid-liquid separation system, the manure was separated into solid part and liquid part. The combination of low CP diet, biofilter for treating the house exhaust air, and additive used for the solid compost part and liquid slurry acidification can achieve a whole chain CH_4 mitigation efficiency of 28.6%. The total GHG of the whole MMC can be reduced by 20%. The whole chain NH_3 can be reduced by 43% (Wang et al., 2017).

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