FINAL REPORT/ 2024203 GREENHOUSE GAS EMISSIONS FROM SUGAR FACTORY BOILERS

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ABSTRACT

Like most industries, the sugar industry is coming under increasing pressure to reduce reportable greenhouse gas emissions. The final report on Australian sugar milling research priorities released in June 2023 identified net zero as a priority area. Measuring and mitigating nitrous oxide (N_2O) emissions was listed as an opportunity and N_2O emissions from boiler stacks were identified as the largest single source of reportable emissions for the milling sector of the industry. Preliminary measurements indicate that the National Greenhouse and Energy Reporting (NGER) emissions factor used to estimate N_2O emissions from bagasse combustion is too high and therefore N_2O emissions from bagasse combustion are being overestimated.

Measurements and calculations carried out during the project strongly suggest that the NGER emission factor used to estimate N_2O emissions from bagasse fired boilers is too high. Based on measurements from 22 boilers firing bagasse across the industry, both the mean (0.64) and the median (0.41) of the calculated emission factors for N_2O from bagasse combustion are well below the NGER emission factor for N_2O from bagasse combustion (1.1). N_2O emission factor results suitable for discussion with regulators are provided.

Several factors that are likely to affect greenhouse gas emissions from sugar factory boilers were identified in this project, but further investigations are required to better understand the processes that contribute to reportable greenhouse gas emissions and how to reduce these emissions.

EXECUTIVE SUMMARY

Like most industries, the sugar industry is coming under increasing pressure to reduce reportable greenhouse gas emissions. The final report on Australian sugar milling research priorities released in June 2023 identified net zero as a priority area. Measuring and mitigating N_2O emissions was listed as an opportunity and N_2O emissions from boiler stacks were identified as the largest single source of reportable emissions for the milling sector of the industry.

Measurements and calculations carried out during the project strongly suggest that the NGER emission factor used to estimate N_2O emissions from bagasse fired boilers is too high. Based on measurements from 22 boilers firing bagasse across the industry, both the mean (0.64) and the median (0.41) of the calculated emission factors for N_2O from bagasse combustion are well below the NGER emission factor for N_2O from bagasse combustion (1.1). N_2O emission factor results suitable for discussion with regulators are provided.

However, for methane (CH_4) the situation is less clear. Based on measurements from the same 22 boilers firing bagasse across the industry, the mean of the calculated emission factors for CH_4 from bagasse combustion (0.47) is more than the NGER emission factor for CH_4 from bagasse combustion (0.3) but the median of the calculated emission factors for CH_4 from bagasse combustion (0.03) is much less than the NGER emission factor for CH_4 from bagasse combustion (0.3). The mean of the calculated emission factor for CH_4 is inflated by a small number of high calculated emission factors. The emissions of CH_4 appear to be strongly affected by combustion conditions and therefore it is not possible at this stage to propose a new emission factor for CH_4 from bagasse combustion.

Measured N_2O and CH_4 concentrations from selected boilers firing bagasse pre and post wet scrubbers indicate that the wet scrubbers used in the Australian sugar industry do not have any statistically significant effect on N_2O and CH_4 emissions. This is consistent with both N_2O and CH_4 having low solubilities in and reactivities with water at the temperatures encountered in standard wet scrubbers. It is therefore unlikely that there will be any dissolved N_2O or CH_4 in scrubber water.

Measurements carried out from 22 boilers firing bagasse across the industry indicate that increasing excess air will increase emissions of N_2O and reduce emissions of CH_4 but due to the large amount of scatter in the data the correlations were quite weak. Measurements carried out on one boiler firing bagasse indicate that increasing the proportion of overfire air will reduce emissions of N_2O and CH_4, but the number of readings was not high enough to make this result statistically significant.

Measurements carried out at a factory with both grate and suspension fired boilers strongly suggest that the grate firing results in higher N_2O emissions than suspension firing. This is consistent with the observation from the combustion literature that combustion of coal in fluidised beds produces significantly more N_2O than combustion of coal in suspension due to the lower temperatures in fluidised bed combustion.

Measurements carried out from 22 boilers firing bagasse across the industry found a very slight negative correlation between N_2O emissions and boiler loading as a percentage of the boiler's maximum continuous rating (MCR). There was essentially no correlation between CH_4 emissions and boiler loading as a percentage of the boiler's MCR.

Analyses of bagasse from three factories and measurements carried out from the boilers at these factories found a strong inverse correlation between the conversion of nitrogen in the bagasse to N_2O and the bagasse oxygen to nitrogen ratios. This is consistent with results reported by others for peat combustion. There was also a reasonably strong correlation between the conversion of nitrogen in the bagasse to N_2O and the median bagasse particle size.

Measurements from one boiler during start-up found that emissions of N_2O were higher during the grate firing stage of boiler start-up and that emission of CH_4 were higher during the suspension firing stage of boiler start-up.

A review of different options for removal of N_2O from boiler flue gas was carried out. Most of the process or technologies that are used to reduce emissions of other nitrogen oxides such as nitric oxide (NO) and nitrogen dioxide (NO_2) were found either to cause no change in N_2O emissions or an increase in N_2O emissions. Some researchers found that staged combustion could reduce N_2O emissions, but other researchers found that staged combustion either had no effect or caused small increased in N_2O emissions. The addition of a second fuel stream after the burnout of the main fuel (reburning) was found by some researchers to significantly reduce N_2O emissions.

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Like most industries, the sugar industry is coming under increasing pressure to reduce reportable greenhouse gas emissions. The final report on Australian sugar milling research priorities released in June 2023 identified net zero as a priority area. Measuring and mitigating N_2O emissions was listed as an opportunity and N_2O emissions from boiler stacks were identified as the largest single source of reportable emissions for the milling sector of the industry. Preliminary measurements indicate that the National Greenhouse and Energy Reporting (NGER) emissions factor used to estimate N_2O emissions from bagasse combustion is too high and therefore N_2O emissions from bagasse combustion are being overestimated.

2 PROJECT OBJECTIVES

Measure emissions of N_2O and CH_4 for a range of different boiler designs across the industry.

Determine effects of boiler operating conditions such as excess air, overfire/underfire air split and steam output on N_2O and CH_4 emissions.

Determine effects of fuel properties such as moisture content, ash content, elemental composition and particle size distribution on N_2O and CH_4 emissions.

Investigate emissions of N_2O and CH_4 during boiler start-up during which the mode of combustion transitions from grate combustion to suspension combustion.

Conduct a literature review to determine the likely effect of wet scrubbing on boiler flue gas N_2O, the likely fate of any N_2O dissolved in scrubber water and whether similar technologies are already utilised for N_2O removal in industry.

Calculate new emission factors for N_2O and CH_4 to allow discussion with the Clean Energy Regulator regarding the potential for more realistic emissions reporting for sugar milling companies.

3 OUTPUTS, OUTCOMES AND IMPLICATIONS

3.1 Outputs

Outputs from the project include measurements of greenhouse gas concentrations and the determination of emission factors for N_2O and CH_4 for roughly half the bagasse boilers in the Australian sugar industry. Preliminary observations about how boiler operating conditions and fuel properties affect greenhouse gas emissions have been made. A new emission factor for N_2O from bagasse combustion has been proposed.

3.2 Outcomes and Implications

Measurements and calculations carried out during the project strongly suggest that the emission factor used to estimate N_2O emissions from bagasse fired boilers is too high. Furthermore, it is reported in the combustion literature that the grab sampling and subsequent analysis approach, as used in this work, is likely to overestimate N_2O emissions.

4 INDUSTRY COMMUNICATION AND ENGAGEMENT

4.1 Industry engagement during course of project

Greenhouse gas measurements were carried out at more than half the factories in the Australian sugar industry. The measurements and calculated emission factors were reported to the factories. Results from the project were reported at the 2025 SRA QUT regional milling research seminars.

4.2 Industry communication messages

Measurements and calculations carried out during the project strongly suggest that the emission factor used to estimate N_2O emissions from bagasse fired boilers is too high. Further work is required to more thoroughly investigate some of the preliminary conclusions from this work.

5 METHODOLOGY

Flue gas samples were collected from 23 boilers (roughly half the boilers in the Australian sugar industry) at Victoria Mill, Inkerman Mill, Kalamia Mill, Pioneer Mill, Mulgrave Mill, Macknade Mill, Invicta Mill, Isis Mill, Racecourse Mill, Plane Creek Mill and Rocky Point Mill. The boilers at these factories have a wide range of steam outputs, operate at different excess air levels and roughly half of them have wet scrubbers installed. One of the boilers is grate fired which was the main mode of combustion in sugar factory boilers over 50 years ago (Lamb, 1979) and is the main mode of combustion in many boilers that burn other types of biomass such as woodchips. The remainder of the boilers in the data set are suspension fired, which is the main mode of combustion in virtually all the currently operating boilers in the Australian sugar industry. One of the boilers was burning woodchips when the flue gas was sampled. The samples were collected at different boiler steam outputs, different excess air levels, different overfire/underfire air splits, upstream and downstream of wet scrubbers and during the different stages of boiler start-up. Fig. 1 shows the flue gas sampling arrangement. A hand pump was used to extract flue gas from various locations around the boilers through a filter and into a syringe. A needle was subsequently placed on the end of the syringe and the flue gas in the syringe chamber was then injected into a pre evacuated vial.

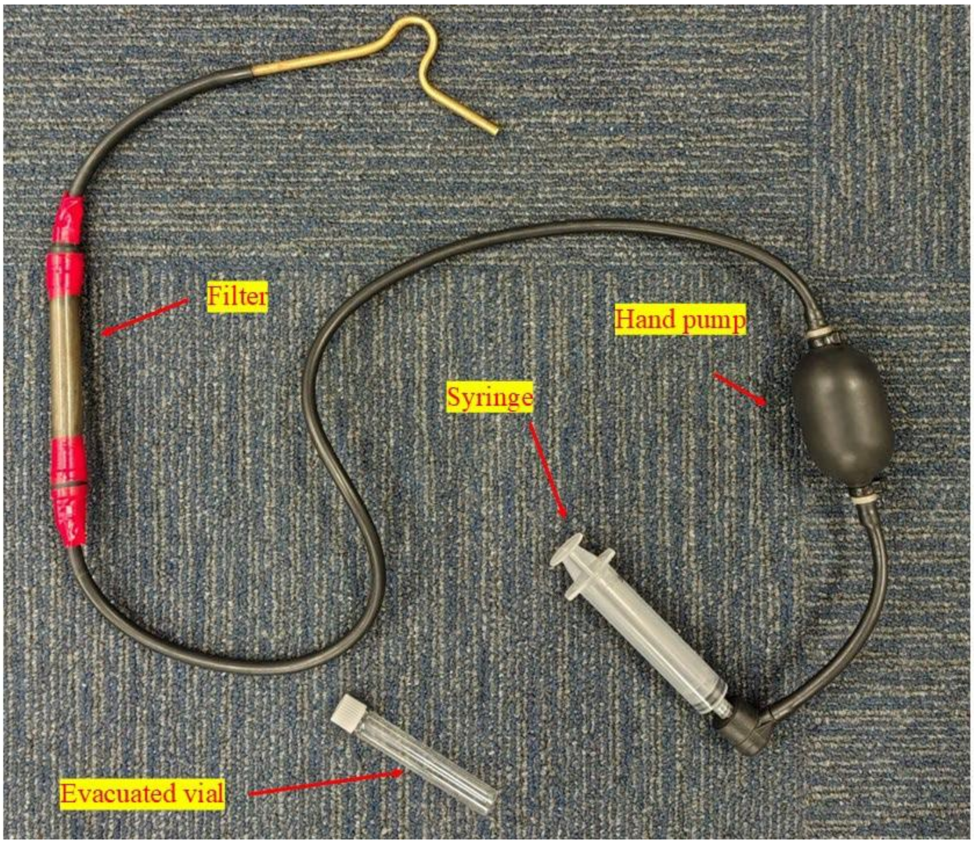

Figure 1 Flue gas sampling arrangement.

The flue gas samples in the vials were subsequently analysed at QUT using gas chromatography–mass spectrometry (GC-MS) to determine the concentrations of N_2O and CH_4.

A portable gas analyser (Testo 350XL) was used to measure the oxygen (O_2) and carbon monoxide (CO) concentrations and gas temperatures at the same locations around the boilers. These measurements were used, along with the boiler steam output recorded by the boiler instrumentation, to estimate the bagasse and flue gas flows through the boilers and therefore the flow rates of N_2O and CH_4 at the measurement locations. The flow rates of bagasse, N_2O and CH_4 and the global warming potentials of N_2O and CH_4 (265 and 28 respectively[1]) were used to calculate emission factors (kg CO_2-e.GJ^{-1}) for N_2O and CH_4 corresponding to each

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[1] https://cer.gov.au/schemes/national-greenhouse-and-energy-reporting-scheme/about-emissions-and-energy-data/global-warming-potential accessed on 26 November 2024.

measurement. Note the emission factor calculations used the assumed bagasse gross calorific value specified in the National Greenhouse and Energy Reporting (Measurement) Determination 2008 (Anonymous, 2008) of 9.6 GJ.t^{-1}.

Bagasse samples were collected from three of the factories for composition and particle size analyses.

6 RESULTS AND DISCUSSION

6.1 Measurements of N_2O and CH_4 concentrations

The measured N_2O and CH_4 concentrations from 22 boilers firing bagasse are summarised in Figs. 2 and 3 respectively. The mean of the measured N_2O concentrations in Fig. 2 is approximately 3.3 ppm dry basis. It should be noted that these readings are likely to overestimates because it has been identified that N_2O can form from NO and NO_2 in the gas sample in the collection containers (Muzio et al., 1991b). More realistic measurements of flue gas N_2O concentrations using a continuous infrared gas analyser yielded much lower N_2O concentrations than the N_2O concentrations determined from subsequent gas chromatographic analyses of grab samples (Muzio et al., 1991b) because with a continuous analyser there is virtually no delay between collection and analysis of the flue gas sample. Measurements using the more realistic continuous infrared gas analyser approach found that the N_2O concentrations from a range of combustion process were mostly less than 5 ppm wet basis (Muzio et al., 1991b). Therefore, it is likely that the actual flue gas N_2O concentrations in those 22 boilers are lower than those shown in Fig. 2.

The mean of the measured CH_4 concentrations in Fig. 3 is approximately 71.9 ppm dry basis. This is higher than expected but it can be seen from Fig. 3 that there are a small number of high measured CH_4 concentrations while most of the measured CH_4 concentrations are quite small.

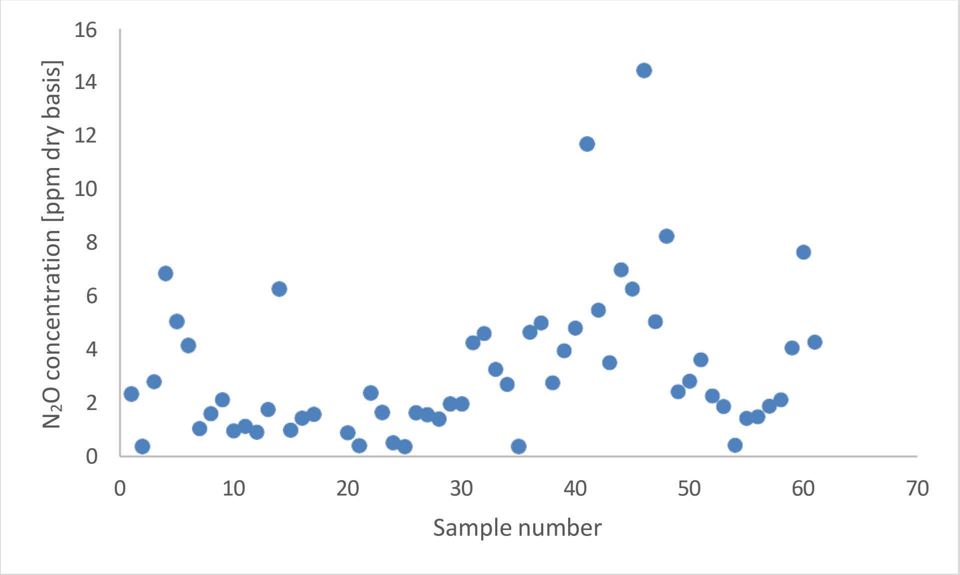

Figure 2 Measured N_2O concentrations (ppm dry basis) from 22 boilers firing bagasse across the industry.

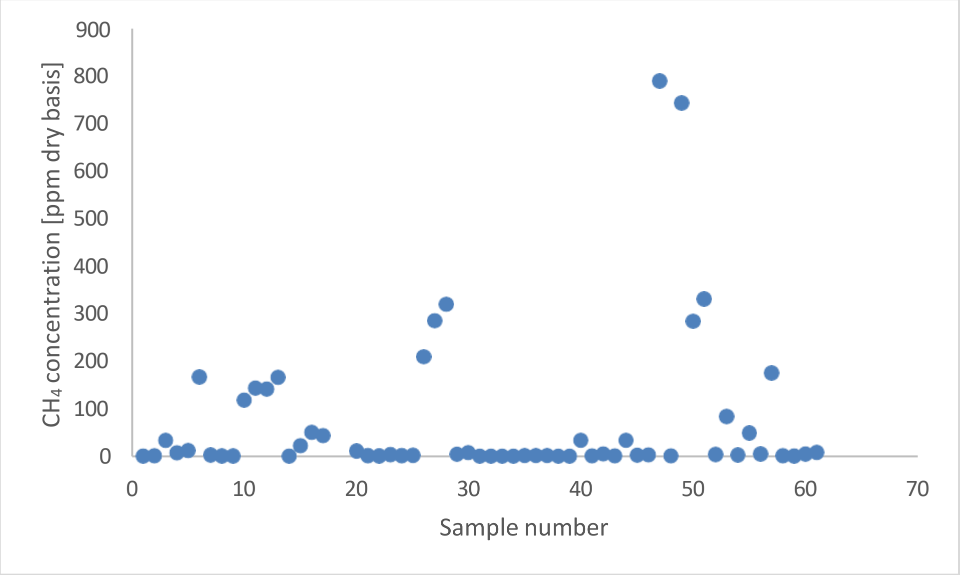

Figure 3 Measured CH_4 concentrations (ppm dry basis) from 22 boilers firing bagasse across the industry.

The emission factors calculated from the measured N_2O and CH_4 concentrations from 22 boilers firing bagasse are summarised in Figs. 4 and 5 respectively. The bagasse combustion emission factors for N_2O and CH_4 (1.1 and 0.3 respectively) specified in the National Greenhouse and Energy Reporting (Measurement) Determination 2008 (Anonymous, 2008) are shown as dashed lines in each of the figures for comparison.

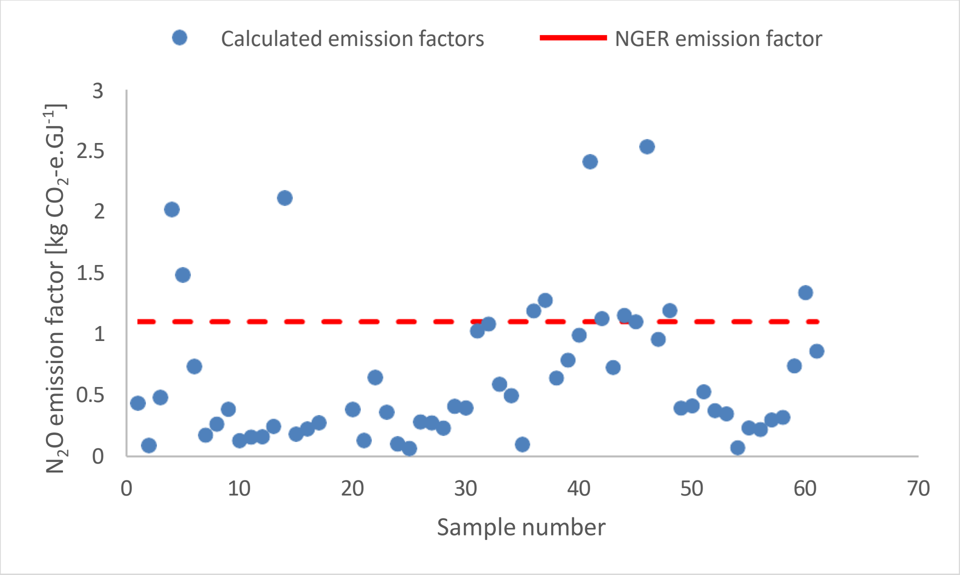

Figure 4 N_2O emission factors calculated from the measured N_2O concentrations from 22 boilers firing bagasse across the industry. The NGER emission factor for N_2O from bagasse combustion (1.1) is shown for comparison.

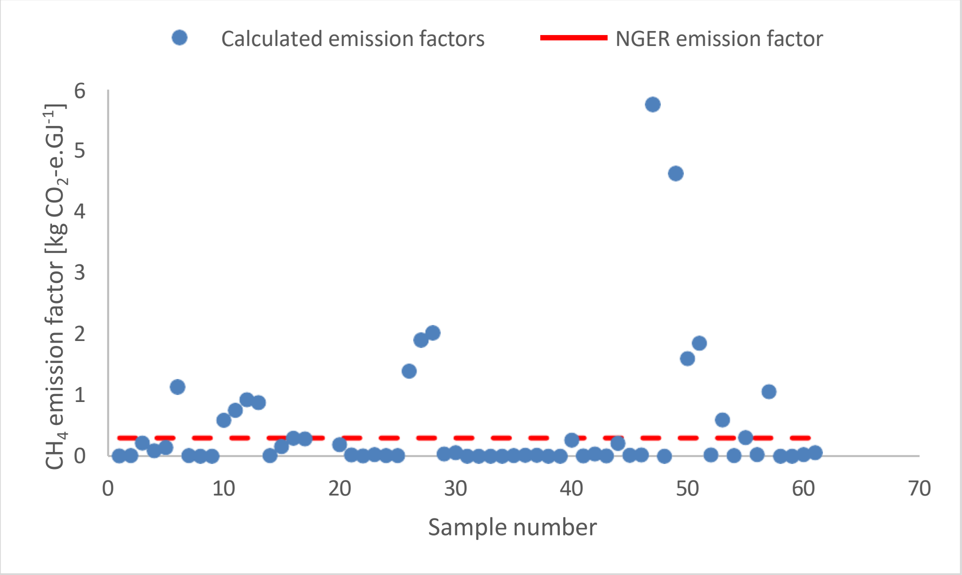

Figure 5 CH₄ emission factors calculated from the measured CH₄ concentrations from 22 boilers firing bagasse across the industry. The NGER emission factor for CH₄ from bagasse combustion (0.3) is shown for comparison.

The mean of the calculated N_2O emission factors in Fig. 4 is 0.64 which is just over half the NGER bagasse combustion emission factor for N_2O (1.1). More than 81% of the calculated N_2O emission factors in Fig. 4 are smaller than the NGER bagasse combustion emission factor for N_2O.

The mean of the calculated CH_4 emission factors in Fig. 5 is 0.47 which is higher than the NGER bagasse combustion emission factor for CH_4 (0.3). Approximately 75% of the calculated CH_4 emission factors in Fig. 5 are smaller than the NGER bagasse combustion emission factor for CH_4. Note that the mean value is inflated by a relatively small number of high readings.

Histograms showing the N_2O and CH_4 emission factor distributions corresponding to Figs. 4 and 5 are shown in Figs. 6 and 7 respectively. The bulk of the emission factors are at the low ends of the respective ranges.

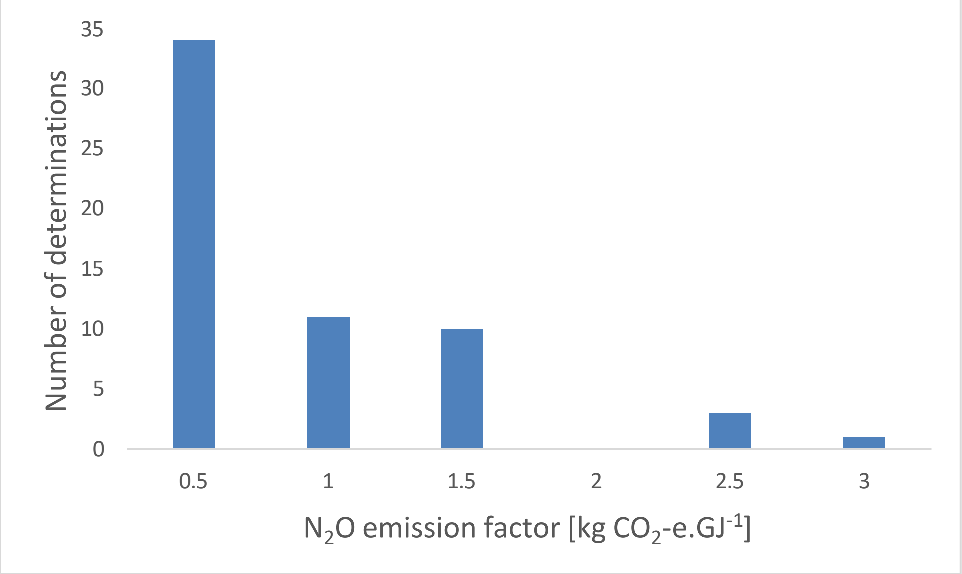

Figure 6 Histogram showing the distribution of N_2O emission factors corresponding to Fig. 4.

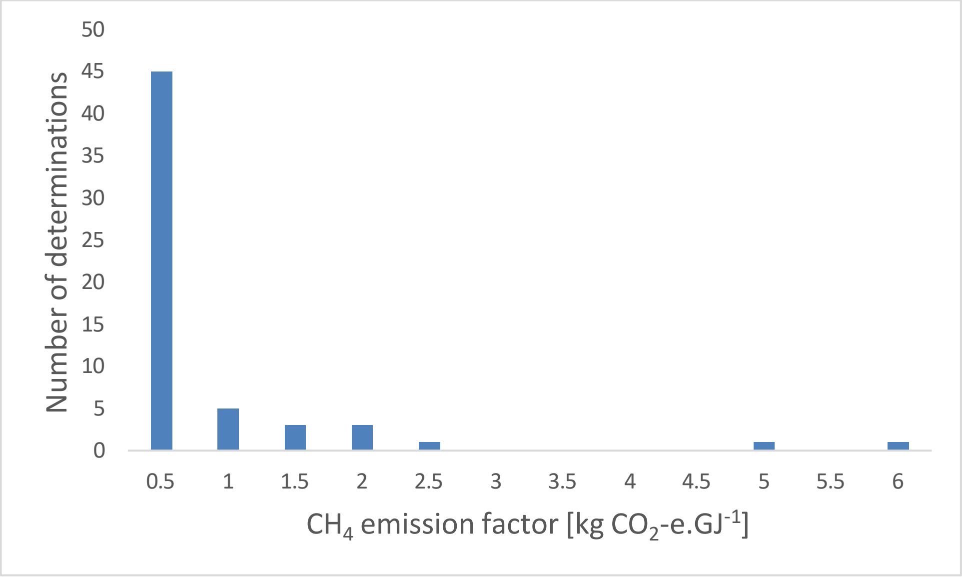

Figure 7 Histogram showing the distribution of CH_4 emission factors corresponding to Fig. 5.

Table 1 shows a summary of the N_2O and CH_4 emission factor distributions from 22 boilers firing bagasse across the industry. For N_2O both the mean (0.64) and median (0.41) emission factors are below the NGER emission factor for N_2O from bagasse combustion (1.1). The standard deviation of the N_2O emission factor distribution is quite high (0.58) due to the large amount of scatter in the data. The skewness of the N_2O emission factor distribution is very high (1.61). For CH_4 the mean emission factor (0.47) is above the NGER emission factor for CH_4 from bagasse combustion (0.3) but the median emission factor (0.03) is well below the NGER emission factor for CH_4 from bagasse combustion (0.3). The standard deviation of the CH_4 emission factor distribution is very high (1.04) due to the very large amount of scatter in the data. The skewness of the CH_4 emission factor distribution is extremely high (3.61).

Table 1 Summary of the N_2O and CH_4 emission factor distributions calculated from the measured N_2O and CH_4 concentrations from 22 boilers firing bagasse across the industry.

		EMISSION FACTOR (KG CO_2-E.GJ^{-1})	
		N_2O	**CH_4**
MEAN		0.64	0.47
STANDARD DEVIATION		0.58	1.04
SKEWNESS		1.61	3.61
	10%	0.13	0.01
PERCENTILES	**50% (MEDIAN)**	0.41	0.03
	90%	1.34	1.60
PERCENTILE OF NGER EMISSION FACTOR (%)		81.4	73.4

6.2 Emission factors for N_2O and CH_4 pre and post wet scrubbers

The emission factors calculated from the measured N_2O and CH_4 concentrations from selected boilers firing bagasse pre and post wet scrubbers are compared in Figs. 8 and 9 respectively.

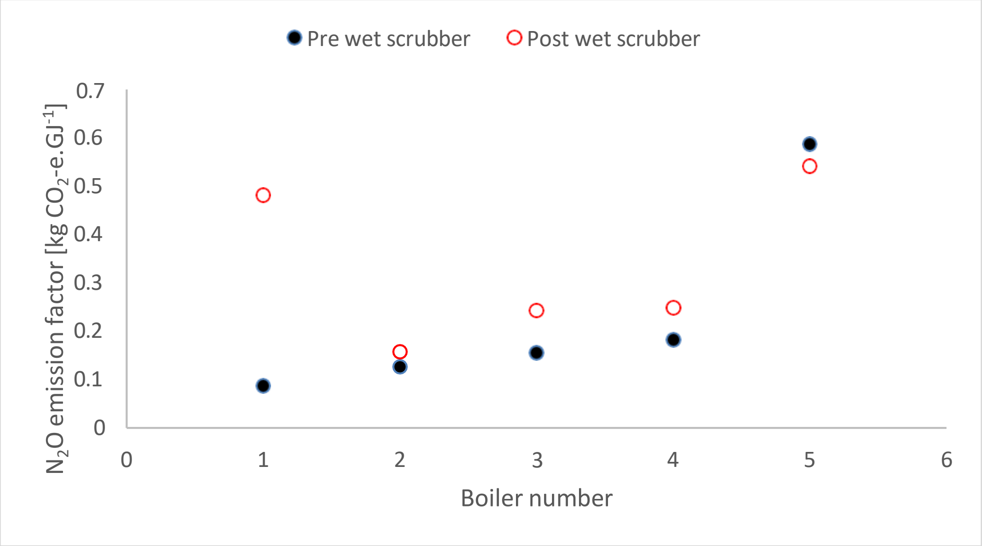

Figure 8 N_2O emission factors calculated from the measured N_2O concentrations from selected boilers firing bagasse pre and post wet scrubbers.

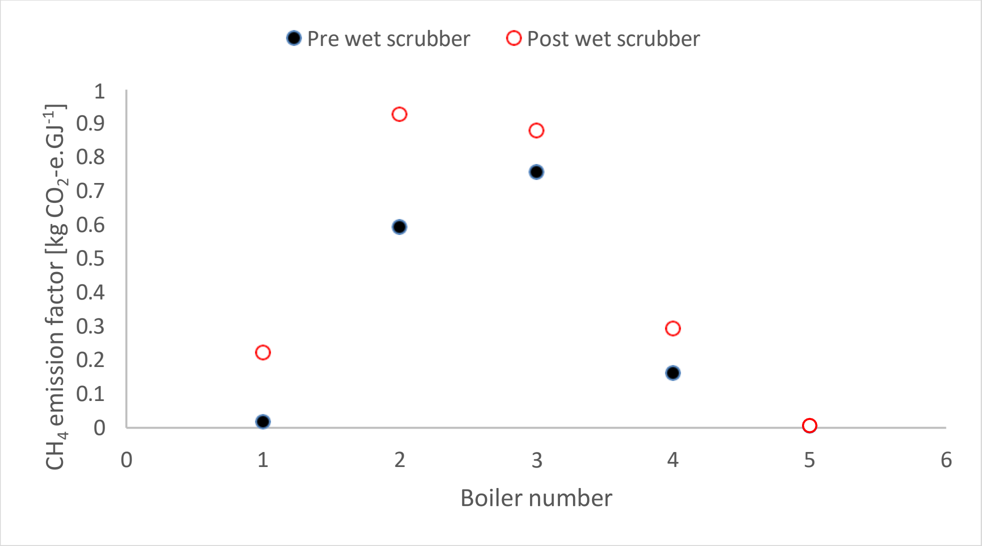

Figure 9 CH_4 emission factors calculated from the measured CH_4 concentrations from selected boilers firing bagasse pre and post wet scrubbers.

From Fig. 8 the N_2O emission factors are higher post wet scrubber than pre wet scrubber in four of the five boilers. A single factor Anova analysis carried out on the N_2O emission factors gave a p value of 0.39 which indicates that the wet scrubbers do not have a statistically significant effect on the N_2O emission factors.

Fig. 9 shows the CH_4 emission factors are higher post than pre the wet scrubber. However, a single factor Anova analysis carried out on the emission factors gave a p value of 0.53 which indicates that this apparent increase in CH_4 emission factors across the wet scrubbers is not statistically significant.

6.3 Effects of excess air, airflow distribution, mode of combustion, steam output and fuel properties on N_2O and CH_4 emissions

6.3.1 *Excess air*

The emission factors calculated from the measured N_2O and CH_4 concentrations for all boilers firing bagasse are plotted against flue gas O_2 concentration (an indicator of excess air) in Figs. 10 and 11. There is a slight positive correlation between the N_2O emission factor and the flue gas O_2 concentration and a slight negative correlation between the CH_4 emission factor and the flue gas O_2 concentration.

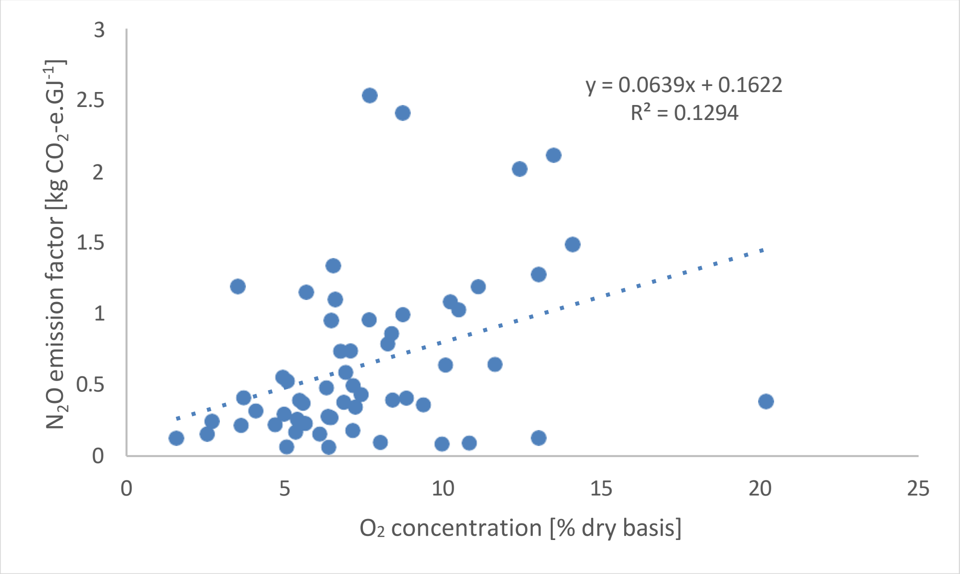

Figure 10 N_2O emission factors calculated from the measured N_2O concentrations plotted against flue gas O_2 concentration (% dry basis) for 22 boilers firing bagasse across the industry.

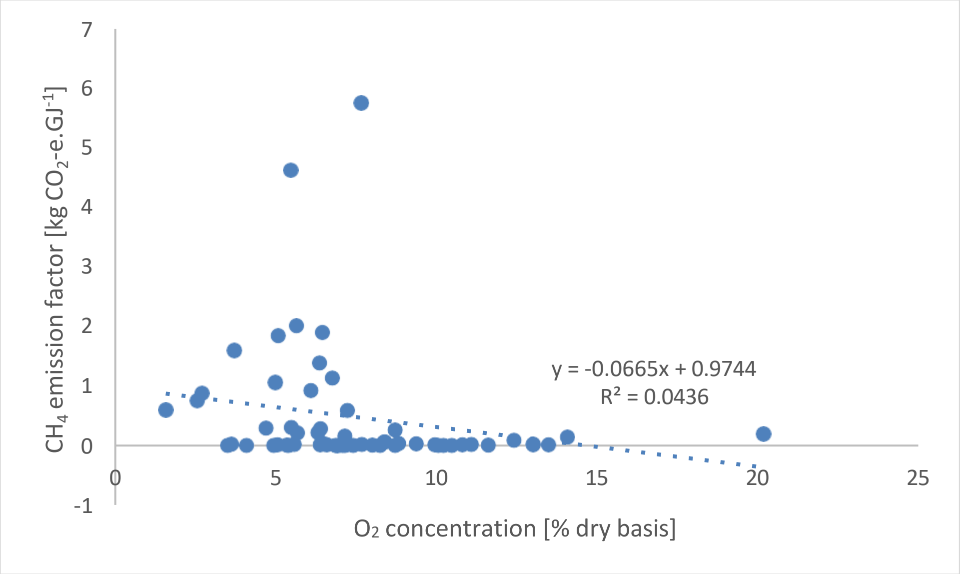

Figure 11 CH_4 emission factors calculated from the measured CH_4 concentrations plotted against flue gas O_2 concentration (% dry basis) for 22 boilers firing bagasse across the industry.

Fig. 12 shows the measured CH_4 concentrations plotted against the measured CO concentrations. There is an approximately linear relationship between most of the CH_4 and CO concentrations.

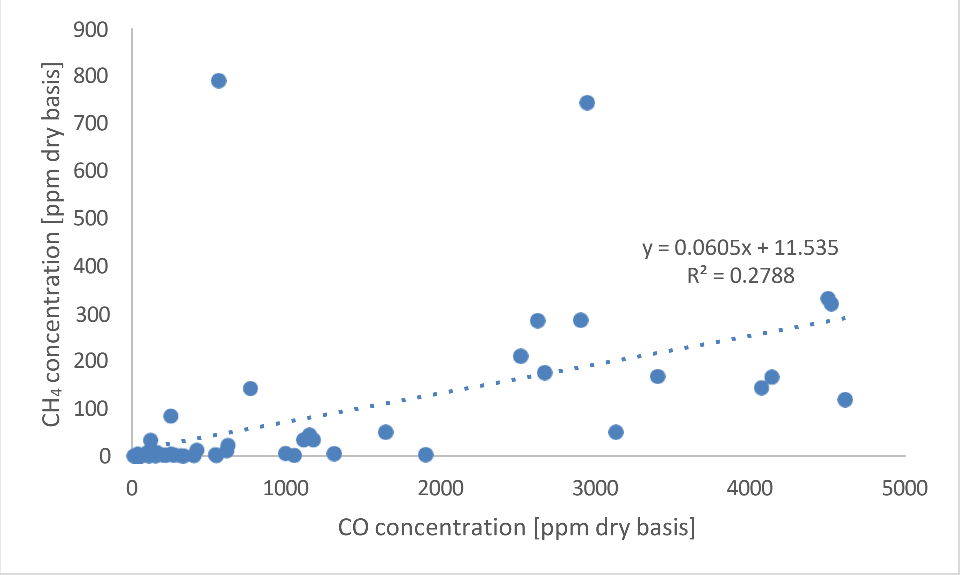

Figure 12 CH_4 concentrations (ppm dry basis) plotted against CO concentrations (ppm dry basis) for 22 boilers firing bagasse across the industry.

6.3.2 *Airflow distribution*

It was only possible to make a significant change to the air flow distribution on one boiler for the purposes of this testing program. Table 2 compares the mean calculated N_2O and CH_4 emission factors based on measurements on this boiler with 50% overfire air and 60% overfire air. The p value calculated from a two-sample t-test with unequal variances (Welch's t-test) are also shown in the table. The mean emission factors for both N_2O and CH_4 both reduce significantly with the increased overfire air but due to the limited number of and variability in the measurements, the p values are much higher than the p value required for these reductions in mean emission factors to be statistically significant (0.05).

Table 2 Mean calculated N_2O and CH_4 emission factors for one boiler with 50% and 60% overfire air. The p values calculated from a two-sample t-test with unequal variances (Welch's t-test) are also shown.

	% OVERFIRE AIR		P VALUE
	50	**60**	
MEAN N_2O EMISSION FACTOR (KG CO_2-E.GJ^{-1})	0.79	0.15	0.35
MEAN CH_4 EMISSION FACTOR (KG CO_2-E.GJ^{-1})	2.32	0.16	0.52

6.3.3 *Mode of combustion*

Table 3 compares the mean calculated N_2O and CH_4 emission factors based on measurements on suspension fired boilers and a grate fired boiler at one factory. The mean calculated N_2O emission factor is significantly higher with grate firing than suspension firing and the p value of 0.08 is close to the value required to be considered statistically significant (0.05). Combustion of coal in fluidised beds produces significantly more N_2O than combustion of coal in suspension due to the lower temperatures in fluidised bed combustion (Hayhurst and Lawrence, 1992). Therefore, it is possible that the higher N_2O emissions with grate bagasse combustion are also due to the lower temperatures.

The mean calculated CH_4 emission factor is lower with grate firing than suspension firing but the p value is 0.59 so this result is not statistically significant.

Table 3 Mean calculated N_2O and CH_4 emission factors for suspension fired boilers and a grate fired boilers at one factory. The p values calculated from a two-sample t-test with unequal variances (Welch's t-test) are also shown.

	FIRING MODE		P VALUE
	SUSPENSION	**GRATE**	
MEAN N_2O EMISSION FACTOR (KG CO_2-E.GJ^{-1})	0.39	1.75	0.08
MEAN CH_4 EMISSION FACTOR (KG CO_2-E.GJ^{-1})	0.29	0.12	0.59

6.3.4 *Steam output*

The emission factors calculated from the measured N_2O and CH_4 concentrations are plotted against the boiler steam output, expressed as a percentage of each boiler's MCR, in Figs. 13 and 14 respectively. There is a very slight negative correlation between the N_2O emission factor and % MCR and essentially no correlation between the CH_4 emission factors and % MCR.

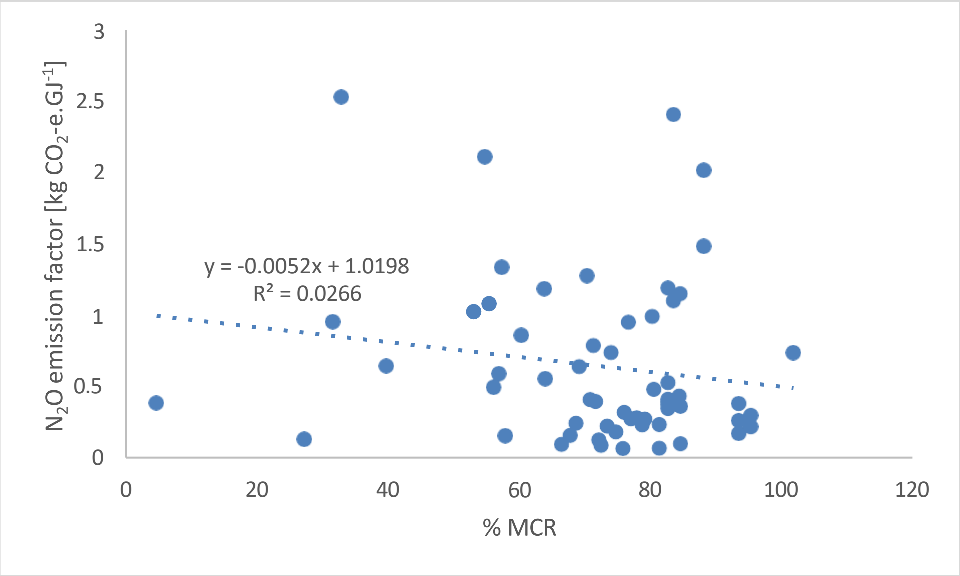

Figure 13 N_2O emission factors calculated from the measured N_2O concentrations plotted against % MCR for 22 boilers firing bagasse across the industry.

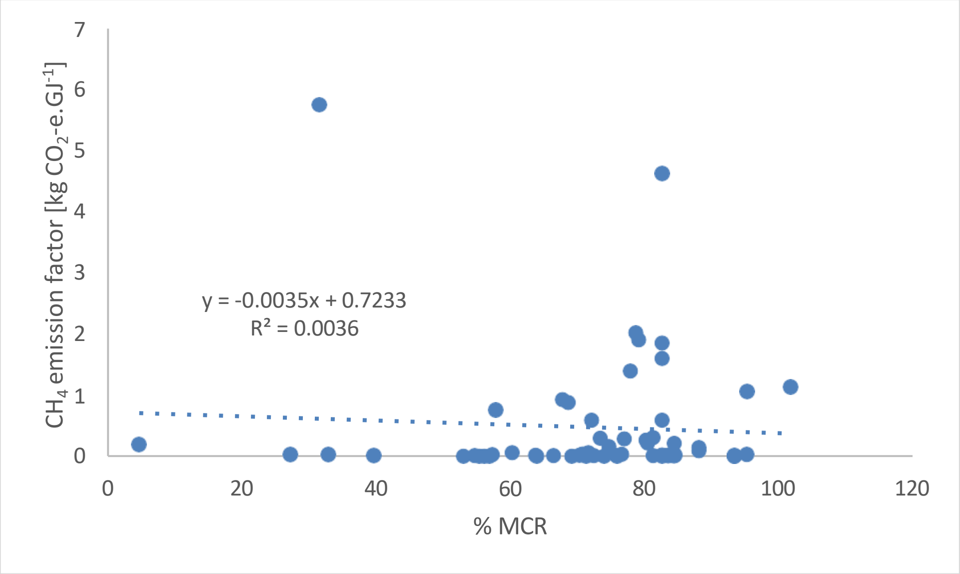

Figure 14 CH_4 emission factors calculated from the measured CH_4 concentrations plotted against % MCR for 22 boilers firing bagasse across the industry.

6.3.5 *Fuel properties*

The analyses of the bagasse samples collected from three factories are summarised in Table 4. There are small variations in the moisture and ash contents, but the ultimate analyses of the samples are similar. This similarity between the bagasse samples contrasts with the wide variation in the calculated N_2O and CH_4 emission factors. Note however that the nitrogen contents of all three bagasse samples are very small, which means that any variations in the nitrogen contents can have a significant effect on oxygen to nitrogen (O/N) ratio of the bagasse sample. The O/N ratios of the bagasse samples in Table 4 range from 142 to 169. Aho and Rantanen (1989) carried out nitrogen oxide measurements on peat samples in an entrained flow reactor and found that the conversion of fuel nitrogen to N_2O was inversely proportional to the fuel O/N ratio. The mean conversions of bagasse fuel nitrogen to N_2O calculated from the measured N_2O concentrations at each of the three factories and the bagasse analyses in Table 4 are plotted against the bagasse fuel O/N ratios in Fig. 15. There is a very strong inverse correlation between conversion of bagasse fuel nitrogen to N_2O and bagasse fuel O/N ratio for these three factories.

Table 4 Bagasse analysis results.

		FACTORY A	FACTORY B	FACTORY C
MOISTURE CONTENT (% WET BASIS)		49.1	51.1	51.2
PROXIMATE ANALYSIS (% DRY BASIS)	**ASH**	9.3	9.1	8.4
	VOLATILE MATTER	80.4	80.7	78.3
	FIXED CARBON	10.3	10.2	13.4
ULTIMATE ANALYSIS (% DRY BASIS)	**C**	45.7	45.9	45.9
	H	5.8	5.8	5.7
	O	38.9	38.92	39.67
	N	0.26	0.23	0.28
	S	0.03	0.04	0.04
	CL	0.01	0.01	0.01
GCV[2] ($MJ.KG^{-1}$) (WET BASIS)		9.1	8.7	8.6

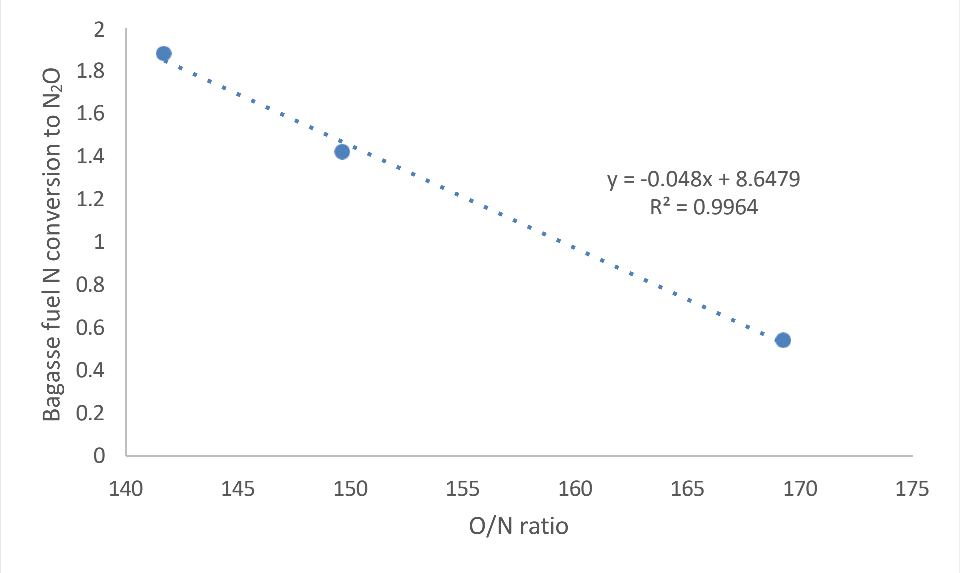

Figure 15 Mean conversions of bagasse fuel nitrogen to N_2O plotted against bagasse fuel O/N ratio for three factories.

Particle size analyses using sieves were carried out on the three bagasse samples, and the particle size information is summarised in Table 5. Cumulative and incremental particle size distributions for the three bagasse samples are shown in Figs. 16 and 17.

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[2] Gross calorific value.

Table 5 Particle size information from the three bagasse samples.

PARTICLE SIZE DISTRIBUTIONS			
SIZE RANGE	**MASS %**		
	FACTORY A	**FACTORY B**	**FACTORY C**
> 4000 µM	60.2	39.0	47.0
< 4000 µM > 2800 µM	2.3	20.7	31.8
< 2800 µM > 1400 µM	0.8	1.4	8.1
< 1400 µM > 710 µM	15.7	13.6	11.5
< 710 µM > 500 µM	12.4	17.2	0.9
< 500 µM > 355 µM	2.3	5.3	0.4
< 355 µM	6.3	2.8	0.3
PARTICLE SIZE DISTRIBUTION PARAMETERS (µM)			
	FACTORY A	**FACTORY B**	**FACTORY C**
MEAN	6734	3367	3936
D_{10}[3]	446	589	1660
D_{50}[4] (MEDIAN)	4044	2687	3785
D_{90}[5]	16 482	7065	6400

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[3] The particle size (µm) below which corresponds to 10% of the sample mass.
[4] The particle size (µm) below which corresponds to 50% of the sample mass.
[5] The particle size (µm) below which corresponds to 90% of the sample mass.

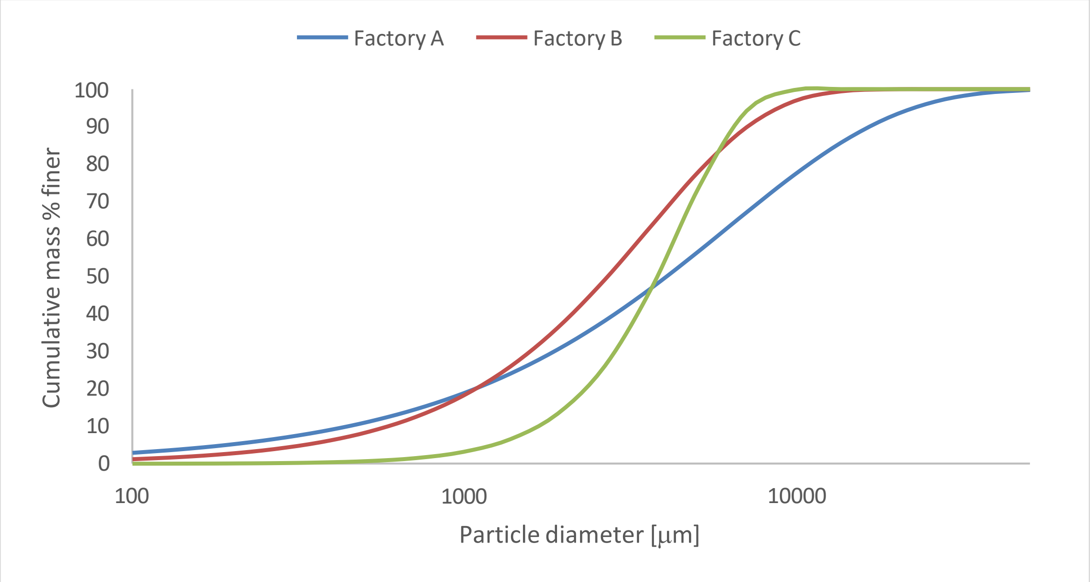

Figure 16 Cumulative particle size distributions calculated from the particle size analyses carried out on the bagasse samples.

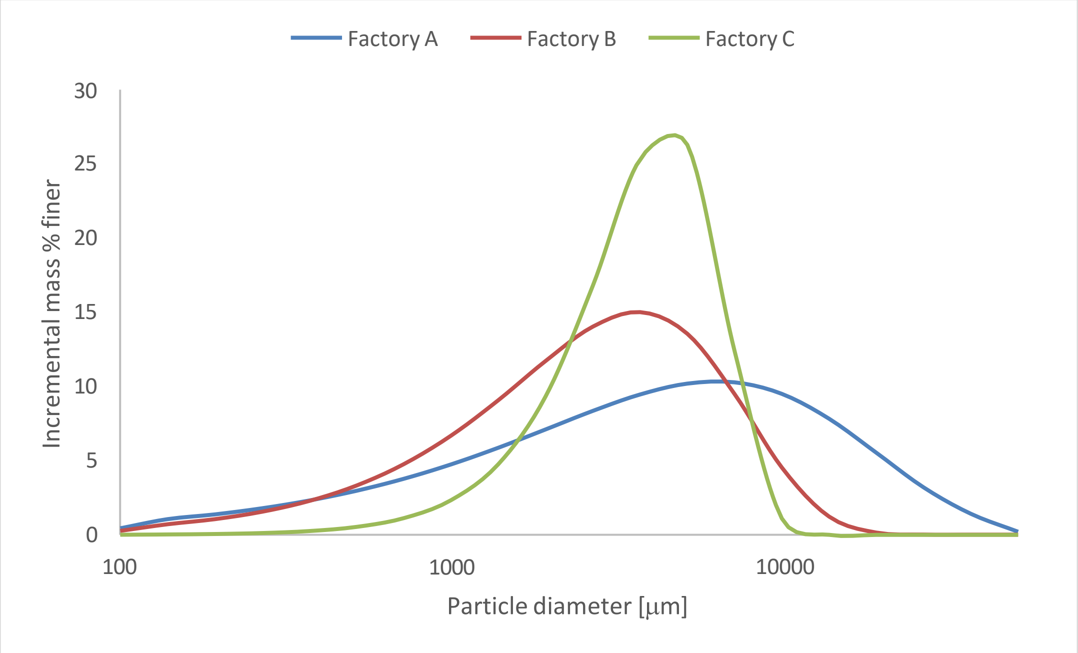

Figure 17 Incremental particle size distributions calculated from the particle size analyses carried out on the bagasse samples.

The mean conversions of fuel nitrogen to N_2O calculated from the measured N_2O concentrations at each of the three factories are plotted against the particle size parameters d_{10}, d_{50} (median) and d_{90} in Figs. 18, 19 and 20 respectively. There is a reasonably strong positive correlation between conversion of bagasse fuel nitrogen to N_2O and the median (d_{50}) particle size for these three factories (Fig. 19). There is very little correlation between conversion of bagasse fuel nitrogen to N_2O and the 90th percentile particle size (d_{90}) (Fig. 20).

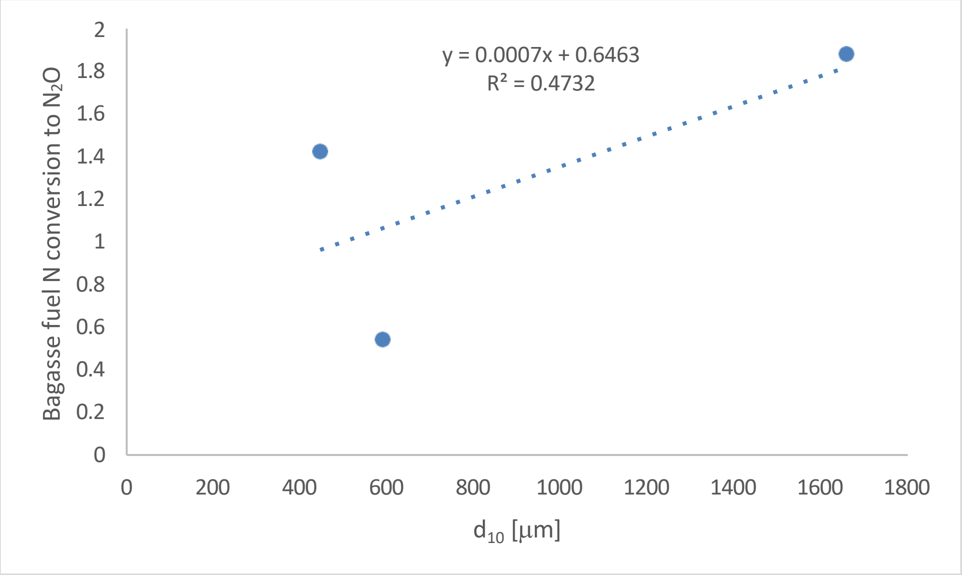

Figure 18 Mean conversions of bagasse fuel nitrogen to N_2O plotted against particle size parameter d_{10} for three factories.

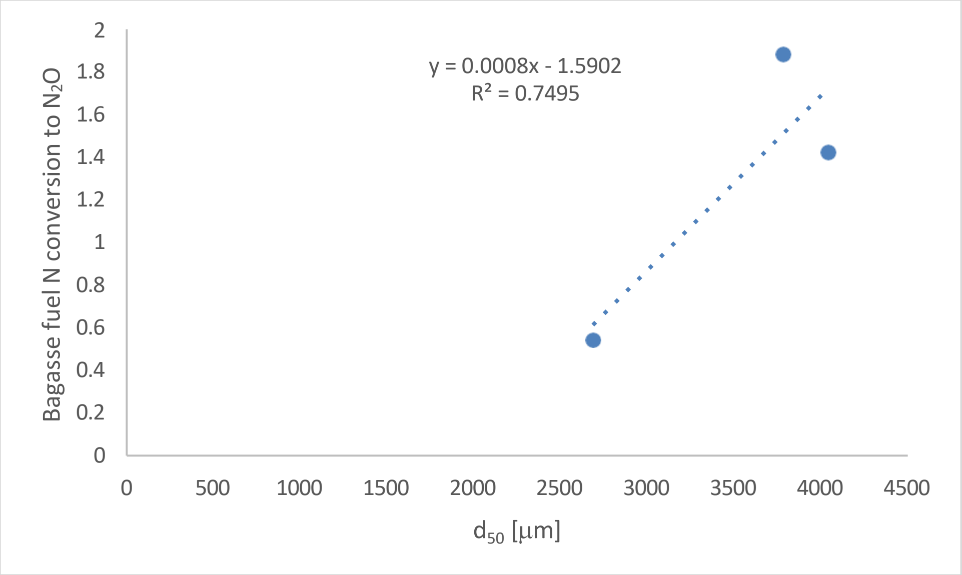

Figure 19 Mean conversions of bagasse fuel nitrogen to N_2O plotted against particle size parameter d_{50} for three factories.

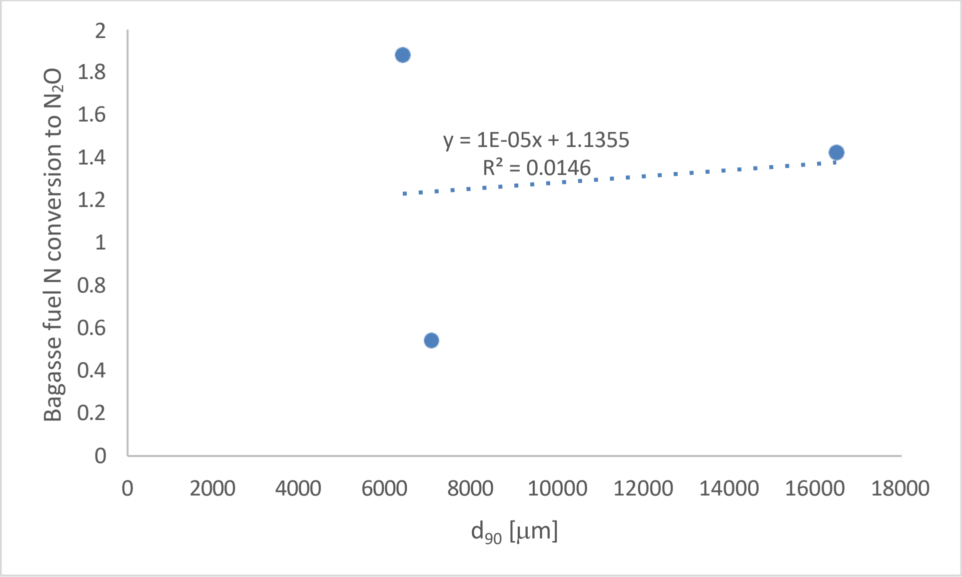

Figure 20 Mean conversions of bagasse fuel nitrogen to N_2O plotted against particle size parameter d_{50} for three factories.

6.4 Emissions profile during start-up

Table 6 summarises the measured concentrations of and calculated emission factors for N_2O and CH_4 during the different stages of the start-up of one boiler. All the values in Table 6 are based on the average of two measurements. Note that it is not possible to calculate an emission factor for the initial light-up stage of a boiler start-up because there is no bagasse flow into the boiler at that time.

Table 6 Measured concentrations of and calculated emission factors for N_2O and CH_4 during the different stages of the start-up of one boiler.

STAGE	CONCENTRATION (PPM DRY BASIS)		EMISSION FACTOR (KG CO_2-E.GJ^{-1})	
	N_2O	CH_4	N_2O	CH_4
LIGHT-UP	5.93	13.36		
GRATE COMBUSTION	1.40	1.78	0.39	0.02
SUSPENSION COMBUSTION	1.09	3.07	0.23	0.02

The measured concentrations of N_2O and CH_4 are very high during light-up stage of boiler start-up. The diesel that is used for light-up is likely to be contributing to these high values. The average of the measured N_2O concentrations and the calculated N_2O emission factor are higher during the grate combustion stage of boiler start-up than for the later suspension combustion stage. The average of the measured CH_4 concentrations is higher during the suspension combustion stage of the boiler start-up.

6.5 Technologies for N_2O removal

There are several techniques that have been used to reduce NO_x emissions from combustion sources. These include (Hayhurst and Lawrence, 1992; Kramlich and Linak, 1994):

- Staged combustion;
- Reburning;
- Selective noncatalytic reduction (SNCR); and
- Selective catalytic reduction (SCR).

Staged combustion involves adjusting the air flow distribution so that the fuel initially encounters a region of reduced oxygen availability so that the conversion of fuel nitrogen to N_2 is improved (Kramlich and Linak, 1994). Cases where staged combustion successfully reduced N_2O emissions in fluidised beds were reported by Hayhurst and Lawrence (1992). However, Kramlich and Linak (1994) reviewed a wider range of studies finding that staging either had no effect or caused small increases or decreases in N_2O emissions. The results in Table 2 where N_2O emissions reduced when the proportion of overfire air increased, suggest that staging may help reduce N_2O emissions, however given this effect is not statistically significant and the inconclusive results from the literature, it is difficult to draw any strong conclusions about the effect staged combustion has on N_2O emissions.

Reburning involves the addition of a second fuel stream after the burnout of the main fuel is achieved. When the primary fuel was coal and the secondary fuel was natural gas reburning was able to reduce N_2O emissions by around 50% (Kramlich et al., 1989; Kramlich and Linak, 1994).

SNCR involves injecting ammonia (NH_3), urea $CO(NH_2)_2$ or cyanuric acid $(HNCO)_3$ into the boiler flue gas to reduce NO_x concentrations. Ammonia injection was found to have either no effect or a small effect on N_2O emissions (Hayhurst and Lawrence, 1992; Muzio et al., 1991a). Cyanuric acid injection was found to cause up to 40% of the NO being converted to N_2O (Muzio et al., 1991a) and the urea injection was found to increase N_2O levels by an amount between these two extremes (Muzio et al., 1991a). There appears to be little scope for reducing N_2O emissions by the application of SNCR to the boiler flue gas.

SCR involves the application of a reducing agent such as ammonia or urea into the flue gas in the presences of a catalyst to reduce NO_x concentrations. The review by Kramlich and Linak (1994) found that SCR with noble metal catalysts may generate significant N_2O emissions and that SCR with vanadium catalysts do not generate significant N_2O emissions. Therefore, SCR with any sort of catalyst does not appear to be an option for reducing N_2O emissions.

Fig. 21 compares the solubilities of N_2O, NO, SO_2 and CH_4 in water for a range of temperatures[6]. Note that these solubilities are for one atmosphere (101.325 kPa) pressure of the respective gases above the solution. The solubilities of NO, N_2O and CH_4 in water are much lower than the solubility of SO_2 in water.

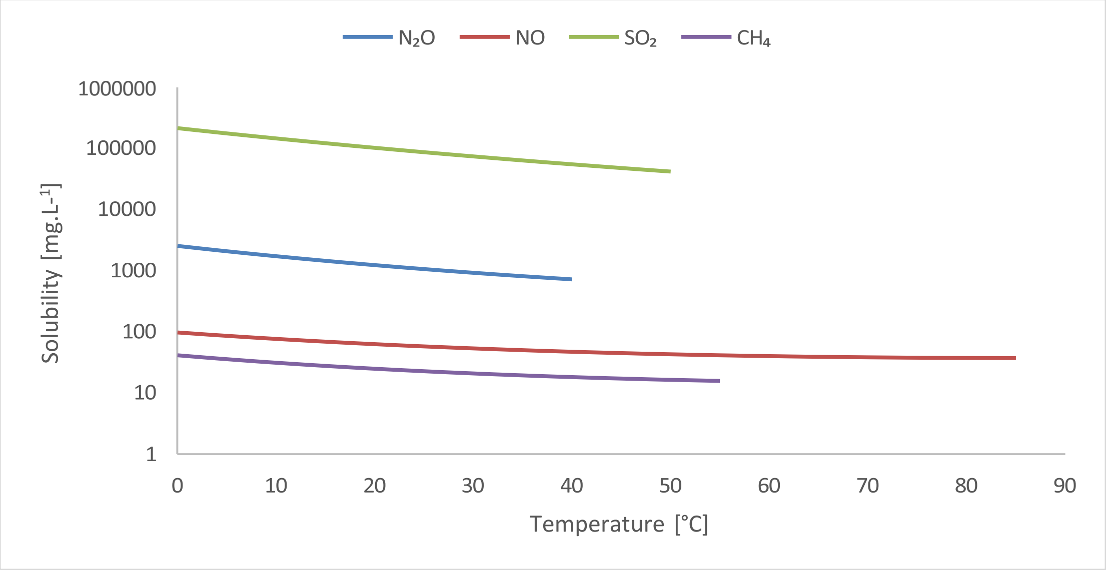

Figure 21 Solubilities of N_2O, NO and SO_2 in water for a range of temperatures[6].

From Fig. 21 the solubility of N_2O in water with one atmosphere pressure above the solution ranges from 727 to 2535 g.L^{-1}. According to Henry's law to solubility of a gas in a solution is proportional to the partial pressure of that gas above that solution. All the N_2O concentrations from bagasse combustion in Fig. 2 are less than 15 ppm dry basis and are even smaller on a wet basis. Making the assumptions of the highest N_2O reading with bagasse

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[6] https://diverdi.colostate.edu/all_courses/CRC%20reference%20data/solubility%20of%20gases%20in%20water.pdf. Accessed on 12 June 2025.

firing and no moisture in the flue gas (i.e. an N_2O concentration in the flue gas of 15 ppm wet basis), then Henry's law gives an upper solubility range for N_2O in water of 0.011 to 0.038 $mg.L^{-1}$. These very low solubilities are consistent with the data in Fig. 8 that show no pattern of standard wet scrubbers reducing N_2O levels in boiler flue gas. The very low solubility of CH_4 in water is also consistent with the data in Fig. 9 that show no pattern of standard wet scrubbers reducing CH_4 levels in boiler flue gas.

Wet scrubbers are effective at removing SO_2 from boiler flue gas because SO_2 has a high solubility in water and because SO_2 reacts with water to produce sulphurous acid (H_2SO_3). Wet scrubbers are also effective at removing NO_x from boiler flue gas, despite NO having low solubility in water, because NO_2 (formed from the oxidation of NO) reacts with water to produce nitric (HNO_3) and nitrous (HNO_2) acid. However, N_2O has both low solubility and low reactivity with water and therefore standard wet scrubbers are much less effective at removing N_2O from boiler flue gas. Therefore, it appears that little, if any of the N_2O produced during combustion will end up in the outflow water from the standard wet scrubbers currently used in the Australian sugar industry.

There are some advanced processes that effectively remove N_2O, such as mediated electrocatalytic reduction (Muthuraman et al., 2019) but this process does not appear to be have been applied to boiler flue gases.

7 CONCLUSIONS

Measurements and calculations carried out during the project strongly suggest that the NGER emission factor used to estimate N_2O emissions from bagasse fired boilers is too high. Based on measurements from 22 boilers firing bagasse across the industry, both the mean (0.64) and the median (0.41) of the calculated emission factors for N_2O from bagasse combustion are well below the NGER emission factor for N_2O from bagasse combustion (1.1). N_2O emission factor results suitable for discussion with regulators are provided.

However, for CH_4 the situation is less clear. Based on measurements from the same 22 boilers firing bagasse across the industry, the mean of the calculated emission factors for CH_4 from bagasse combustion (0.47) is more than the NGER emission factor for CH_4 from bagasse combustion (0.3) but the median of the calculated emission factors for CH_4 from bagasse combustion (0.03) is much less than the NGER emission factor for CH_4 from bagasse combustion (0.3). The mean of the calculated emission factor for CH_4 is inflated by a small number of high calculated emission factors. The emissions of CH_4 appear to be strongly affected by combustion conditions and therefore it is not possible at this stage to propose a new emission factor for CH_4 from bagasse combustion.

Measured N_2O and CH_4 concentrations from selected boilers firing bagasse pre and post wet scrubbers indicate that the wet scrubbers used in the Australian sugar industry do not have any statistically significant effect on N_2O and CH_4 emissions. This is consistent with both N_2O and CH_4 having low solubilities in and reactivities with water at the temperatures encountered in standard wet scrubbers. It is therefore unlikely that there will be any dissolved N_2O or CH_4 in scrubber water.

Measurements carried out from 22 boilers firing bagasse across the industry indicate that increasing excess air will increase emissions of N_2O and reduce emissions of CH_4 but due to the large amount of scatter in the data the correlations were quite weak. Measurements carried out on one boiler firing bagasse indicate that increasing the proportion of overfire air will reduce emissions of N_2O and CH_4, but the number of readings was not high enough to make this result statistically significant.

Measurements carried out at a factory with both grate and suspension fired boilers strongly suggest that the grate firing results in higher N_2O emissions than suspension firing. This is consistent with the observation from the combustion literature that combustion of coal in fluidised beds produces significantly more N_2O than combustion of coal in suspension due to the lower temperatures in fluidised bed combustion.

Measurements carried out from 22 boilers firing bagasse across the industry found a very slight negative correlation between N_2O emissions and boiler loading as a percentage of the boiler's MCR. There was essentially no correlation between CH_4 emissions and boiler loading as a percentage of the boiler's MCR.

Analyses of bagasse from three factories and measurements carried out from the boilers at these factories found a strong inverse correlation between the conversion of nitrogen in the bagasse to N_2O and the bagasse oxygen to nitrogen ratios. This is consistent with results reported by others for peat combustion. There was also a reasonably strong correlation between the conversion of nitrogen in the bagasse to N_2O and the median bagasse particle size.

Measurements from one boiler during start-up found that emissions of N_2O were higher during the grate firing stage of boiler start-up and that emission of CH_4 were higher during the suspension firing stage of boiler start-up.

A review of different options for removal of N_2O from boiler flue gas was carried out. Most of the process or technologies that are used to reduce emissions of other nitrogen oxides such as NO and NO_2 were found either to cause no change in N_2O emissions or an increase in N_2O emissions. Some researchers found that staged combustion could reduce N_2O emissions, but other researchers found that staged combustion either had no effect or caused small increased in N_2O emissions. The addition of a second fuel stream after the burnout of the main fuel (reburning) was found by some researchers to significantly reduce N_2O emissions.

8 RECOMMENDATIONS FOR FURTHER RD&A

Several preliminary conclusions have been drawn from the measurements and calculations carried out in this work. However, the validity of some of these conclusions is affected by the large amount of scatter in the data. More measurements are required under, preferably, more controlled conditions to isolate the important factors that increase greenhouse gas emissions so that mitigating strategies can be implemented.

There is very little published work on N_2O and CH_4 emissions from bagasse fired boilers. More fundamental studies on this are required.

9 PUBLICATIONS

Nil.

10 ACKNOWLEDGEMENTS

The assistance provided by factory staff with the measurements is greatly appreciated. Christian Brunk of QUT for providing sampling advice and evacuated vials for the project. Pamela Limpin of the Central Analytical Research Facility (CARF) at QUT is acknowledged for carrying out the GS-MS analyses of the flue gas samples. Neil McKenzie of QUT is acknowledged for providing advice on bagasse particle size analyses.

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12 APPENDIX

12.1 Appendix 1 METADATA DISCLOSURE

<Delete these guidelines prior to submission. Please do not change font styles. Fill in the following details regarding the data generated in the course of this project. Provide details about the location, accessibility and contact details of those managing the data. Delete if not required.>

TABLE 7 METADATA DISCLOSURE 1

Data	(Description)
Stored Location	(I.e. organisation and server)
Access	(I.e. publicly accessible or restricted? Please provide details.)
Contact	(I.e. Details of person/position with access)

TABLE 8 METADATA DISCLOSURE 2

Data	(Description)
Stored Location	(I.e. organisation and server)
Access	(I.e. publicly accessible or restricted? Please provide details.)
Contact	(I.e. Details of person/position with access)

12.2 Appendix 2

13 SRA RESEARCH MISSIONS MANAGER’S RECOMMENDATION

(To be completed by the SRA Research Missions Manager, Research Investments)

Milestone Number			
Milestone Title	Final Report		
Final Report Due Date		Date submitted	
		Date of submission of revised version (if relevant)	
Date Reviewed		Date of review of revised version (if relevant)	
Reason for delay **(if relevant)**			
Milestone Payment			
Total Project Funding by SRA-RMS			
Project Objectives **(Contracted)**			
Success in achieving the objectives	☒ Completely Achieved ☐ Partially Achieved ☐ Not Achieved		

SRA Research Missions Manager’s comments:

Project Outputs (brief version)

Activities to further develop, disseminate, commercialise or exploit the Project Outputs (after discussion with CI)

Recommendation: