Co-combustion of Biosolids with Wood Pellets in a Wood Pellet Stove

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Abstract- **Co-combustion of biosolids with coal or other biomass fuel can play a significant role in combustion facilities for energy production and waste management policy context. This paper presents the results of an experimental study to investigate the use of biosolids for co-combustion with wood pellets in a wood pellet stove. Fuel property, gas emissions and stove efficiency are compared. In regard to fuel properties, proximate analysis, ultimate analysis and heating values are determined and emissions of carbon monoxide (CO), nitrogen oxides (NOx) and sulphur dioxide (SO$_2$) are measured and compared. Pilot scale combustion tests revealed that co-combustion of 10% biosolids with 90% wood pellets resulted in successful combustion without any significant degradation of efficiency and emissions. Nitrogen oxides (NOx) emissions were found to be proportional with the N$_2$ content in the fuel. Sulphur dioxide (SO$_2$) emissions were negligible.**

Index Terms- **Biosolids, co-combustion, wood pellet stove, performance and emissions.**

I. INTRODUCTION

Sewage sludge refers to the solids separated during the treatment of municipal wastewater. According to United States Environmental Protection Agency (US EPA), biosolids refers to treated sewage sludge that meets the EPA pollutant and pathogen requirements for land application and surface disposal. Gomez et al. [1] reported that the production of dry biosolids ranges from 20-32.85 kg per person per year. Present options for biosolids management in Europe, North America, and Japan or in other countries mainly consist of land application, landfilling and incineration or co-combustion. Land application, landfilling and incineration represented 80% of biosolids use in the United States in 2004 [2]. Due to stricter regulations concerning landfilling and land application it can be expected that there will be an increase in the role of incineration in the long term [3]. Incineration as a competitive treatment option for biosolids management is reported in several recent studies [4] – [9].

Cherubini et al. [4] performed life cycle assessment to compare the environmental impact of incineration and the landfilling of municipal solid waste in Sao Paulo City, Brazil. The results showed that a shift in waste treatment from landfilling to incineration would decrease the overall environmental impact.

A study by Houillon and Jolliet [5] quantified the environmental impact of six processes used for wastewater urban sludge treatment: agricultural land spreading of limed pasty sludge; specific incineration in fluidized bed of pasty sludge; wet oxidation of liquid sludge; pyrolysis of dried sludge; incineration in cement kilns of dried sludge; and landfill of limed pasty sludge. The study showed that for global warming, incineration in cement kilns has the best balance while

landfill and agricultural spreading have the worst.

Lundin et al. [6] have assessed the environmental and economic consequences of four recycling and disposal options for municipal sewage sludge. The four options were: agricultural application, co-combustion with waste, combustion combined with phosphorus recovery and fractionation including phosphorus recovery. The economic assessment showed that agricultural application had the lowest cost of the options, however transportation distance largely affects the cost of this option. Alternatively, co-combustion had the best energy balance with the least emissions. The application of sludge on agricultural land was the least preferable option from an environmental perspective.

Apedaile [7] presented a scenario of biosolids management options and their share in Canada. The share of different options was: incineration (47%), land application (43%), reclamation and other uses (6%) and landfill (4%). Incineration was suggested as a promising alternative to land application in another Canadian study performed by Davis et al. [8]. Dewatered biosolids are being successfully incinerated in a number of plants in different countries in full compliance with current air emission requirements. Davis et al. [8] indicated that techniques are available to meet even more stringent air emission requirements that may be put in place in the future. Energy recovery in the form of heat or electricity is possible and practiced to varying degrees depending on the economic case. In Germany, for example, electrical power produced as part of an energy recovery system commands a higher sale price from utilities than 'conventional' power, which makes co-generation using biosolids as the energy source more attractive.

Otero et. al. [9] reported co-combustion of sewage sludge with coal. When the weight percentage of sludge in the blend was ⩽10%, the effects on the combustion of coal were hardly noticeable. Spliethoff et. al. [10] tested sewage sludge, wood and straw co-combustion with coal. In the case of sewage sludge, the high content of volatile matter resulted in an accelerated combustion process. Owing to their high volatile matter content, sewage sludge, straw and wood are suited for application in air and fuel staging with a view to nitrogen abatement.

An integrated appraisal of five technology scenarios for the co-combustion of biosolids in the UK energy and waste management policy context is presented by Cartmell et al. [11]. The scenarios were: (i) Scenario 1, co-combustion with coal in a third party large scale combustion facility with no participation of the water utility in power generation or sale. (ii) Scenario 2, co-combustion with wastes at a third party energy-from-waste (EfW) facility. (iii) Scenario 3, co-combustion with wastes at an EfW facility operated by the water utility. (iv) Scenario 4, co-combustion with supplementary fuel (plant biomass) at a water utility combustion facility with possible third party involvement. (v) Scenario 5, co-combustion in a cement kiln or other industrial user of power and/or heat (CHP). All scenarios provided a net energy gain (0.58-5.0 kWh/kg dry solids), having accounted for the energy required for transportation and sludge drying. Scenario 1 was found a cost-effective economically feasible option for biosolids management.

Co-combustion of biosolids with coal is found a cost-effective option [11]. This study investigated the technical feasibility of using biosolids as a partial substitute of wood pellets using combustion study in facilities where wood pellets are used. As wood pellets are costlier than biosolids, a partial substitution of wood pellets by biosolids would be cost-effective. The combustion efficiency and gas emissions from different ratios of biosolids to wood pellets are measured and compared with that of wood pellets.

II. MATERIALS AND METHODS

A. Biosolids

The remainder of this paper presents a description of biosolids used in this study and the results of combustion and emission

tests performed using a conventional wood stove. This study used biosolids as a fuel for co-combustion with biomass fuels. N-Viro systems Canada LP supplied the biosolids. The following is a short description of biosolids process.

The process involves mixing sewage sludge with an alkaline admixture, principally kiln dust and fly ash, and then subjecting the mixture to a controlled period of storage and mechanical turning and drying as illustrated in Figure 1. The sewage sludge is mechanically dewatered. Alkaline admixtures (AA), usually industrial by-products such as cement kiln dust, lime-kiln dust, fly ash and/or steel-making fines supplemented in some cases with quicklime, are then mixed with the dewatered sludge. The admixtures are dosed at a rate of 20 to 60 percent of the wet-weight sludge depending on the amount of heating required, the type of sludge (the higher the solids content the lower the AA dosage) and the characteristics of the alkaline admixture.

Following the combination of alkaline admixture with the sludge, the mixture is placed in a pile and heated by the exothermic chemical reaction (the 'Heat Pulse') between the sludge and the alkaline admixture. A minimum temperature of 52℃ is maintained for at least 12 hours and the pH of the mixture is maintained above 12 for at least 72 hours. After maintaining the required temperature for 12 hours, the mixture typically is laid out uncovered in windrows approximately four to six feet high and ten to twelve feet wide. During this time, the pH of the mixture is maintained above 12 for at
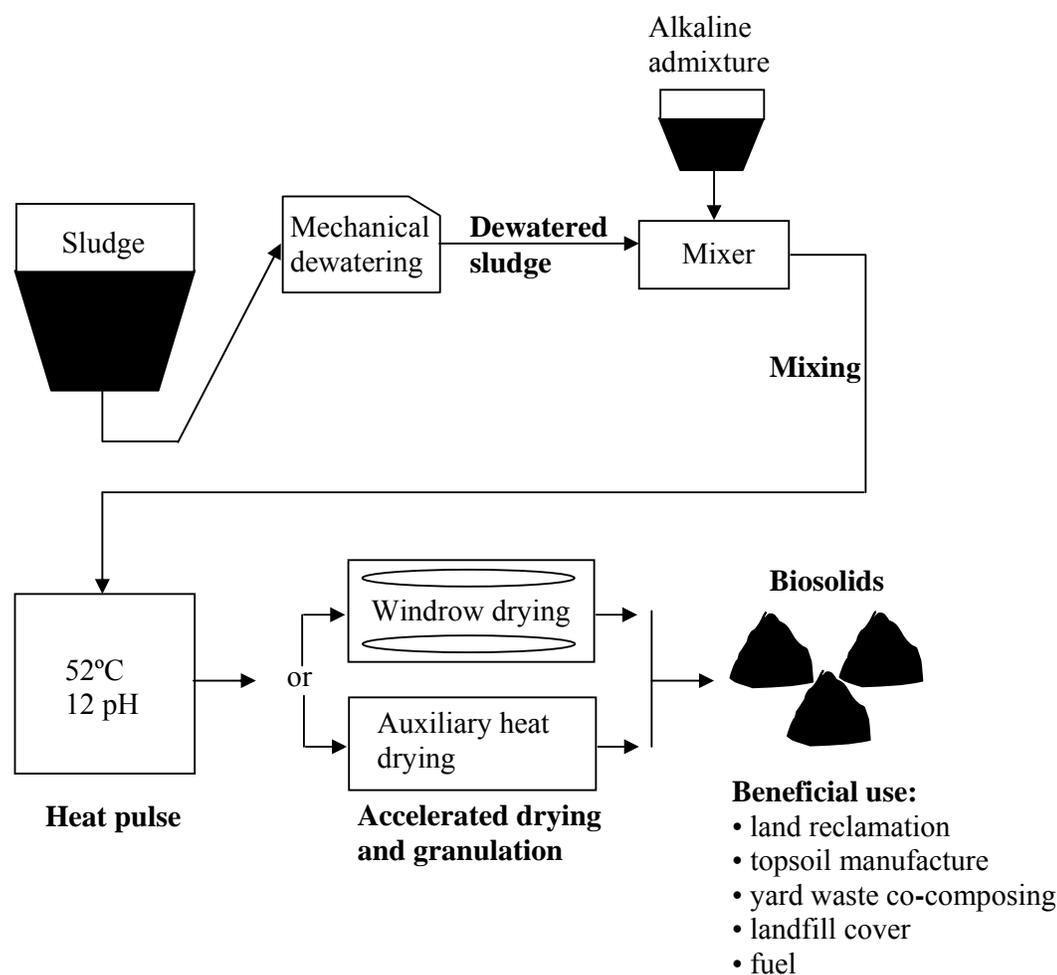

Fig. 1: Biosolids process

least an additional 60 hours. The process is regulated under 40 CFR Part 503 rules as Alternative 2 (temperature > 52° C for 12 hours, pH > 12 for 72 hours, and solids > 50 %). Windrows are intermittently turned to promote drying, increase granulation and prevent compaction until the solids content reaches and maintains a minimum of 50%. When these criteria are met, the product satisfies EPA standards. This biosolid is used as the fuel for co-combustion with biomass pellets for this study.

Initial experiments involved laboratory analysis of fuel characteristics through proximate analysis, ultimate analysis and higher heating value determination of different fuels. After fuel characterization, the biosolids were tested in a small wood pellet stove for combustion and emission analysis. Biosolids were co-fired with wood pellets up to a maximum ratio of 50%.

Three different data samples were obtained for each test point with the exception of ultimate analysis, where two data samples were taken. The average of each data set is shown in the tables. Similar conditions were maintained for all tests to allow a better comparison of the results. The standard deviations of important performance and emission parameters are: 0.55% for overall efficiency, 4.32 ppm for CO, 1.4 ppm for NOx and 0.8 ppm for SO_2.

B. Experimental Apparatus and Test Procedure

A DROLET freestanding wood pellet stove (Eco-35) with 2.4-10.25 kW output capacity was used to perform the combustion experiments. The fuel sources consisted of premium wood pellets and biosolids-wood pellet combinations. The stove is comprised of: (1) a hopper, (2) an auger with auger motor, (3) a burn pot, (4) a control board (touch screen), (5) a full size ash drawer, (6) A cleaning access panel, (7) fresh air intake, (8) air supply control, (9) igniter, (10) convection and exhaust blowers and (11) thermistors and switches. The specifications of Eco-35 stove are presented in Table 1.

C. Thermal Analysis of Combustion

The purpose of thermal analysis of combustion is to determine the overall efficiency and different losses. Efficiency can be tested by the direct method where the energy gain of the working fluid is compared with the energy content of the fuel, and by the indirect method where the efficiency is the difference between the losses and the energy input. This study used the indirect method to calculate overall efficiency. The following are the pertinent losses.

1) % Heat loss due to dry flue gas (dry flue loss) = m_{dry} x C_p x (T_g-T_a) x $100/HHV$; where m_{dry} is the mass of dry flue gas in kg/kg of fuel, C_p is specific heat of flue gas in kCal/kg ºC, T_g is flue gas temperature in ºC, T_a is ambient air temperature in ºC and HHV is higher heating value in kCal/kg.

2) % Heat loss due to wet flue gas (wet loss) = $(m_{moisture})$ x $(h_g$ at T_g-h_f at ambient temperature) x $100/HHV$; where $m_{moisture}$ is the sum of water vapor produced from hydrogen in fuel, moisture present in fuel and moisture present in air in kg/kg of fuel, h_g is enthalpy of steam at the temperature T_g in kCal/kg and h_f is enthalpy of water at ambient temperature in kCal/kg.

3) % Heat loss due to partial conversion of C to CO (CO loss) = [%CO x C/(%CO + %CO_2)] x [5744/HHV] x 100; where 5744 is heat loss (in kCal) due to partial combustion of carbon (C). C is carbon content in kg/kg of fuel; HHV is in kCal/kg.

4) Radiation and unaccounted loss. This is taken as 2% (ABMA chart and experience).

Overall efficiency by indirect method = 100 - (sum of losses).

Theoretical (stoichiometric) air fuel ratio and excess air supplied were determined first for computing the losses. Theoretical air required for combustion is determined from stoichiometric calculation with fuels ultimate/proximate analysis data. Excess air is measured from flue gas analysis. Dry flue gas loss is the greatest loss and can be

Table 1: Specifications of Eco-35 stove

Parameters	Unit	System/values
Heat output	kW	2.4-10.25
Hopper capacity	kg	16
Burn rate	kg/hr	0.59-2.04, six heat settings
Ignition system	-	Electronic
Maximum recommended heating area	sq. m	150
Exterior dimensions	cm × cm × cm	56.52 W × 63.98 D × 72.39 H
Approved vent diameter	cm	7.62-10.16
Electrical requirement	-	120 VAC-60 hz-15 A
Type of door	-	Glass with cast iron frame
Glass type	-	Ceramic glass
Glass surface	sq. cm	664.5
Weight	kg	86.18

calculated from mass of dry flue gas, specific heat of flue gas, and the difference between flue gas temperature and ambient temperature. Wet flue gas loss is the second largest loss. Water vapor is produced from hydrogen in fuel, moisture present in fuel and air during the combustion. The losses due to these components are separately calculated and their sum is taken as wet flue gas loss. Loss due to CO production is also calculated. The share of CO in flue gas loss is very small in most cases. However, with 50% wood pellet and 50% biosolids CO loss is 1.59%. A typical radiation and unaccounted loss of 2% is assumed. It should be noted that presently so called combustion efficiency of the boiler is determined by flue gas analyzer such as by Atkins et al. [12] and Gonzalez et al. [13]. This does not give the actual overall efficiency of the system. The gas analyzer only accounts for dry flue gas loss using Siegert's formula. The Siegert's formula is-

$$S_L = \left(T_{gas} - T_{amb}\right) \bullet \left(\frac{A1}{CO_2} + B\right)$$

where:

S_L- chimney loss- the percentage of heat produced in combustion process which is convected with the combustion gases.

T_{gas}- flue gas temperature

T_{amb}- the temperature of the boiler inlet air (it is assumed by the analyzer to be the ambient temperature).

CO_2- the calculated (on the basis of oxygen concentration and CO_{2max}) amount of CO_2 in combustion gases, expressed in % vol.

A1, B- factors characteristic for a given fuel type.

Based on the calculated chimney loss the analyzer estimates the efficiency of the combustion process η.

$$\eta = 100\% - S_L$$

where: η - combustion efficiency.

Wet flue gas loss is a significant loss in the case of biomass combustion. Atkins et al. [12] has shown efficiencies greater than 82% and Gonzalez et al. [13] greater than 91%. This study presents actual overall efficiency considering all losses.

D. Emission Measurements

After achieving steady state operation with stable flue temperatures, gas emissions were measured using a Unigas 3000[+] flue gas analyzer. The gas composition O_2, CO_2, CO, NO, NOx and SO_2 were measured. The measurement principles of the gas analyzers are electrochemical for O_2, CO, NO, NO_2 and SO_2, and calculated for CO_2 and NOx.

III. RESULTS AND DISCUSSION

At a constant fuel flow rate (1.2 kg/hr), the performance was tested under steady state condition. Steady state was considered when there was almost no change or fluctuation in flue gas temperatures and emission parameters. It took almost 30 minutes to reach steady state condition. Table 2 shows the results of fuel characterization (proximate and ultimate analysis and higher heating value). Sewage sludge and biosolids show very high levels of moisture and ash content. Similar moisture and ash content data were reported in [11] and [14], where raw sludge contained 75% moisture and biosolids contained 40% ash. It can be seen from Table 2 that biosolids have the lowest heating value (approximately 20% of wood pellets) due to higher ash and moisture content. Therefore, no sustainable combustion was possible using biosolids only. More than 50% of biosolid material is ash however, this ash content can be reduced by adding lime (calcium oxide, CaO) with biosolids instead of cement kiln dust (CKD) as an alkaline admixture, as lime has higher pH value than CKD. Saturated lime has a pH value of 12.4, whereas calcium carbonate, the largest share in CKD has a pH of 9.4 [15]. Here, cost might be a concern that needs to be considered.

Tables 3 and 4 show combustion and emission data for different fuels. It was found that co-firing 5% biosolids with 95% wood pellets produced very similar overall efficiency and CO emissions 22% lower than 100% wood pellets. NOx emission increased from 18 ppm for 100% wood pellets to 25 ppm for 5%-95% biosolids-wood pellet combination. Wood pellets did not produce any SO_2, whereas 5%-95% biosolids-wood pellet combination produced only 2 ppm of SO_2. With 10%-90% biosolids-wood pellet combination, overall efficiency decreased by only 1.4%, but CO decreased by 25% of that found with wood pellets. NOx emission increased to 30 ppm, but SO_2 remained at 2 ppm level with 10%-90% biosolids-wood pellet combination. A combination of 20% biosolids and 80% wood pellets and 50% biosolids and 50% wood pellets showed a significant degradation of efficiency and emissions. The decrease in efficiency was over 4% and 11% for 20% and 50% biosolids, respectively. The lowest CO of 135 ppm for 10%-90% biosolids-wood pellet combination and the highest CO of 703 ppm for 50%-50% biosolids-wood pellets were observed. The decrease in CO emissions for 10%-90% biosolids-wood pellet combination is thought to be due to the lower carbon content of biosolids (biosolids contains only

Table 2: Ultimate analysis, proximate analysis and the higher heating value (HHV) of sewage sludge, biosolids and wood pellets

Analysis	Different Fuels		
Ultimate analysis, db (%)	**Sewage sludge**	**Biosolids**	**Wood pellet**
Carbon	16.36	13.82	48.75
Hydrogen	6.25	2.28	6.54
Nitrogen	0.97	0.74	0.05
Sulphur	0.33	0.94	0.24
Oxygen (by difference)	60.82	29.38	44.10
Proximate analysis (%)			
Moisture (as received)	71.25	29.35	5.00
Ash (db)	15.27	52.84	0.32
Volatile matter (db)	78.33	45.44	89.80
Fixed carbon (db)	6.40	1.73	9.88
HHV, as received (kCal/kg)	1329	808	4516

db: Dry basis, HHV: Higher Heating Value

Table 3: Overall efficiency and losses for different fuels

Fuel type	Overall eff. (%)	Dry flue loss (%)	Wet gas loss (%)	CO loss (%)	Radiation & unaccounted loss (%)	Total loss (%)
Premium wood pellet	62.24	23.00	12.35	0.41	2	37.76
Biosolids 5% + pellet 95%	61.84	23.30	12.54	0.32	2	38.16
Biosolids 10% + pellet 90%	61.36	23.43	12.90	0.31	2	38.64
Biosolids 20% + pellet 80%	59.66	23.67	14.11	0.56	2	40.34
Biosolids 50% + pellet 50%	54.17	24.40	17.84	1.59	2	45.83

Table 4: Emissions and temperatures for different fuels

Fuel type	O_2 (%)	CO_2 (%)	Flue temp. (^oC)	Ambient temp. (^oC)	CO (ppm)	NOx (ppm)	SO_2 (ppm)
Premium wood pellet	16.2	4.8	190	20	181	18	0
Biosolids 5% + pellet 95%	16.3	4.7	188	20	141	25	2
Biosolids 10% + pellet 90%	16.5	4.5	186	20	135	30	2
Biosolids 20% + pellet 80%	16.8	4.2	167	20	247	40	2
Biosolids 50% + pellet 50%	18.3	2.7	126	20	703	57	3

28% C of of wood pellet) maintaining good combustion, whereas the highest CO for 50%-50% biosolids-wood pellets is due to inefficient combustion due to high moisture and ash content as well as very low heating value of the tested biosolids, for which the flame temperature became low. However, higher NOx was produced with a higher percentage of biosolids in the fuel mixture. This is thought to be due to higher N_2 content of biosolids.

The three main reasons for NOx formation during biomass combustions reported in [16] - [19] are: thermal NOx (formed from atmospheric nitrogen, above 1300°C), the prompt NOx (formed at the flame front) and the fuel-NOx (formed from elemental nitrogen contents of the fuel). However, at temperatures below 1300°C only fuel-NOx is expected as described in [17] and [18] which is usually the case for small domestic stoves. Therefore, the lowest NOx emissions from wood pellets and the highest NOx emissions in the case of 50%-50% biosolids-wood pellets were probably a consequence of the smallest and largest elemental nitrogen

content of these fuels, respectively. Similar results of NOx increase with higher biosolids addition to biomass were reported in [10]. Spliethoff et al. [10] also reported higher SO_2 emissions with higher percentage of biosolids in biomass, however this study showed negligible SO_2 emissions due to low combustion temperature. Ash production increased with an increase in biosolids in the fuel mixture, for example ash is increased from 0.3% for wood pellets to 4% for a 10% biosolids to 90% pellet ratio, where the efficiency decrease was only 1.4%.

IV. CONCLUSIONS

This paper presents the results of a study to investigate the potential use of biosolids as a partial substitute for wood pellets in combustion facilities. The results include energy values, efficiency and emissions obtained from laboratory analysis and combustion tests performed on a wood pellet stove. Sewage sludge could be a potential fuel if the moisture content can be removed economically. Drying by exhaust heat could be a potential and economically feasible option.

The biosolids tested in this study cannot provide self-sustained combustion in its present form due to its low heating value and high moisture and ash content. High ash content is an unwelcome byproduct. However, co-combustion of a small portion of biosolids with wood pellets showed great potential in terms of combustion efficiency and gas emissions. Biosolids up to 10% mixed with wood pellets can be burned without any significant degradation of efficiency and emissions. However, it is recommended to conduct a further detailed tests to evaluate emissions such as particulate matters (PM), dioxin, furan and poly aromatic hydrocarbons (PAH).

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