Assessing Alternative Options for Energy Cost Reduction in Greenhouse Industry

by

Prabahar Ravichandran

Submitted in partial fulfilment of the requirements

for the degree of Master of Science

at

Dalhousie University

Halifax, Nova Scotia

November 2013

TABLE OF CONTENTS

LIST OF TABLES vii

LIST OF FIGURES ix

ABSTRACT ix

LIST OF ABBREVIATIONS USED xiii

ACKNOWLEDGEMENTS xiv

CHAPTER 1 INTRODUCTION 1

CHAPTER 2 LITERATURE REVIEW 4

2.1 Background 4

2.2 Greenhouse Technology 6

- 2.2.1 Lighting 6
- 2.2.2 Heating 7
- 2.2.3 Cooling and Ventilation 8
- 2.2.4 CO_2 Enrichment 8

2.3 Biomass 9

- 2.3.1 Biomass Composition 11
- 2.3.2 Biomass Densification 12
- 2.3.3 Emissions from Biomass 13

2.3.4 Combustion Technologies 15

CHAPTER 3 OBJECTIVES 18

CHAPTER 4 MATERIALS AND METHODS 19

4.1 Greenhouse Inventory and Energy Cost Breakdown 19

4.1.1 Energy Audit Methodology 20

4.1.2 Benchmarking Indices 22

4.1.3 Energy Cost Breakdown 22

4.1.4 Energy Monitoring System 23

4.2 Biomass Feedstocks Used in This Experiment 23

4.3 Feedstock Pre-processing 24

4.4 Pellet Combustion Experiment 25

4.4.1 Pellet Production 26

4.4.2 Agro Pellet Boiler 28

4.4.3 Experimental Design 29

4.4.4 Gaseous emissions measurement Methodology 32

4.4.5 Particulate emissions measurement Methodology 33

4.5 Hot Water Leaching Experiment 35

4.6 Briquette Combustion Experiment 36

4.6.1 Leaching (washing) 36

4.6.2 Briquetting 36

4.6.3 Experiment Design 39

4.7 Analytical Methods **40**

CHAPTER 5 STATISTICAL ANALYSIS **43**

5.1 Emissions and combustion performance of agro-pellets against premium wood pellets **43**

5.1.1 Feed Auger Calibration 43

5.1.2 Gaseous and Particulate Matter Emissions 44

5.2 Controlled batch Leaching Conditions for optimal Upgrading of Agricultural Biomass **46**

5.3 Comparison of Gaseous and Particle Emissions from Leached and Un-leached biomass briquettes in a Domestic Wood Stove **48**

CHAPTER 6 RESULTS AND DISCUSSIONS **51**

6.1 Greenhouse Inventory **51**

6.2 Benchmarking Greenhouse Operations **51**

6.2.1 Energy Utilization Index (EUI) 51

6.2.2 Energy Cost Index (ECI) 52

6.3 Energy Cost Breakdown **53**

6.3.1 Lighting 53

6.3.2 Ventilation and Cooling 54

6.3.3 Heating 55

6.3.4 Others 56

6.4 Energy Monitoring in Greenhouse Operation 2 (Case Study) **56**

6.4.1 Heating System Monitoring with WELServer 56

6.4.2 Boiler Assessment with Grass Pellet Fuel 58

6.5 Emissions and combustion performance of agro-pellets against premium wood pellets 61

6.5.1 Fuel Pellet Properties 61

6.5.2 Profile of Flue Gas Parameters 62

6.5.3 Gaseous Emissions 64

6.5.4 Particulate Emissions 65

6.5.5 Combustion Performance 66

6.6 Controlled batch Leaching Conditions for optimal Upgrading of Agricultural Biomass 67

6.6.1 Energy Crop 69

6.6.2 Agricultural Residue 71

6.7 Comparison of Gaseous and Particle Emissions from Leached and Un-leached biomass briquettes in a Domestic Wood Stove 78

6.7.1 Fuel Briquettes Properties 78

6.8 Flue Gas Parameters Profile 80

6.9 Gaseous Emissions 81

6.10 Particle Emissions 84

6.11 Contrasts 84

6.12 Combustion Performance 87

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS 89

7.1 Conclusions 89

7.2 Recommendations for Future Work 93

REFERENCES 95

APPENDIX A 105

APPENDIX B 108

APPENDIX C 111

LIST OF TABLES

Table 1. EUI and ECI for commercial greenhouse operations 4,5,6,7 and 8. 52

Table 2. Average of flue gas parameters measured from Pleco Boiler for wood and grass pellet fuel. 60

Table 3. Flue gas emissions normalized to 13% O_2 (ref.) 60

Table 4. Results of proximate analysis and ultimate analysis on wood, barley straw, reed canary grass, switch grass and wheat straw. 61

Table 5. Results of gaseous and particulate emissions on wood, barley straw. Reed canary grass, switch grass and wheat straw. 64

Table 6. Ultimate analysis for the samples used, expressed as percentage of initial dry mass and chlorine expressed in parts per million (ppm). 68

Table 7. Ash analysis and alkali metal composition for the samples, expressed in milligram per gram of dry sample. 68

Table 8. Energy Crops (Switch Grass and Reed Canary Grass) – Mean (μ) and standard deviation (σ) for Ash, K, Na, Mg, Ca, S and N presented for different temperature and resident time combinations. SG – Switch Grass; RC – Reed Canary Grass. 70

Table 9. Agricultural Residue (Barley and Wheat) – Mean (μ) and standard deviation (σ) for Ash, K, Na, Mg, Ca, S and N presented for different temperature and resident time combinations. B – Barley; W – Wheat; 72

Table 10. Proximate analysis results with higher heating value and bulk density of leached and un-leached briquettes. *79*

Table 11. Ultimate and Elemental Analysis results of leached and un-leached briquettes *79*

Table 12. Gaseous emission and other flue gas parameters are presented along with Total Suspended Particulates for the biomass briquettes under study. *84*

Table 13. Contrasts and percentage change comparing the fuel properties of leached and un-leached biomass. *85*

Table 14. Contrasts and percentage change comparing the flue gas parameters and particulate emissions for leached and un-leached briquettes *85*

Table 15. Inventory data collected during initial visits. It presents general information on greenhouse size, months of operation, infrastructural information, lighting, heating, CO_2 injection, irrigation, cooling and ventilation (continued). *105*

LIST OF FIGURES

Figure 1. Feedstock preprocessed in a Supreme Enviro pull type TMR mixer. *24*

Figure 2. Chopped feedstock fed into New Holland hammer mill to reduce feedstocks into fine fibers. *25*

Figure 3. LM72A – Pellet Mill, Lawson Mills Biomass Solutions, Prince Edward Island. *27*

Figure 4. Pellets (bottom row) and hammer milled feedstock (bottom row) from which pellets were produced. (Left to right) Barley straw, Reed canary grass, Switch Grass and Wheat straw. *28*

Figure 5. Agro-Pellet Boiler designed by LST Energy Inc., Pictou County, Nova Scotia. *31*

Figure 6. Eurotron Unigas 3000+ flue gas analyzer installed in the Exhaust of the Agro *32*

Figure 7. Sampling train (Left) and Control Console (Right) of Clean Air EPA Method 5 Particulate matter analyzer. *34*

Figure 8. Front View of Wiema C 150 briquette machine. *37*

Figure 9. Grass briquettes (bottom row) made from un-leached and leached biomass feedstock (top row). Left to right: Unleached reed canary grass; Leached reed canary grass; Unleached switch grass; Leached switch grass. *38*

Figure 10. Straw briquettes (bottom row) made from un-leached and leached biomass feedstock (top row). Left to right: Unleached wheat straw; Leached wheat straw; Unleached Barley straw; Leached barley straw. *38*

Figure 11. Drolet XV Stove with ambers from wood before introducing biomass briquettes *39*

Figure 12. WELServer Schematic representation of Greenhouse Operation #2 .... *57*

Figure 13. Graph showing the profile of flue gas parameters during the steady state combustion of wood. *62*

Figure 14. Graph showing the profile of flue gas parameters during the steady state combustion of wheat straw *63*

Figure 15. A fraction of solid mass collected from the burn pot during the combustion of agro-pellets (Reed Canary pellets). *66*

Figure 16. % reduction in Ash and other inorganic elements with respect to Resident time and Temperature factor. Treatments within a feedstock with same letters are not significantly different. Each column represents % reduction for each resident time and temperature factor combination. *78*

Figure 17. Graph that shows the profile of flue gas parameters during the combustion of leached barley briquettes. *81*

Figure 18. Scatter plot between NOx emission in ppm and fuel bound nitrogen content. 83

Figure 19. Graph representing the differences in flue gas parameters and total suspended particulates between leached and un-leached briquettes. (in a pair of columns, columns

with same letters are not significantly different and columns with different letters are significantly different.) *86*

ABSTRACT

Nova Scotia has over 100 commercial greenhouses covering an area of 186,245 square meters. Heating costs have become the largest energy expenditure in greenhouses mainly due to increasing fuel prices and the use of imported fuel oils. Increasing fuel prices combined with a growing desire to stabilize energy supply has led to a renewed interest in alternative fuel options for greenhouse heating. Agricultural or herbaceous biomass has the potential to become a sustainable and cost effective heating option for the greenhouse industry. Although high inorganic content create challenges during the combustion of herbaceous biomass, these crops create an opportunity if sufficient land mass is available for greenhouse growers to meet their own fuel needs. This research will review energy use and operational practices in the greenhouse industry to identify energy saving opportunities. This study will further investigate biomass feedstocks, processing and combustion technologies suitable for heating greenhouse industry in Nova Scotia.

LIST OF ABBREVIATIONS USED

ANOVA – Analysis Of Variance

BD – Bulk Density

CFL – Compact Fluorescent Lamp

ECI – Energy Cost Index

EEF – Energy Efficiency Measures

EMO – Energy Management Opportunity

EPA – Environmental Protection Agency

ESP – Electro Static Precipitators

EUI – Energy Use Index

FIT – Feed in Tariff

GHG – Greenhouse Gases

HPS – High Pressure Sodium

NS – Nova Scotia

PAR – Photosynthetically Active Radiations

SRC – Short Rotation Coppices

WEL – Web Energy Logger

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr. Kenny Corscadden for his direction throughout and my supervisory committee members Dr. Ilhami Yildiz and Dr. Quan (Sophia) He.

I would also like to extend my thanks to the other faculty members and staff for their help and advice. Special thanks to greenhouse operators who supported me during visits and data collection.

CHAPTER 1 INTRODUCTION

Extreme temperatures and changing weather patterns are important factors limiting agricultural production in Nova Scotia. Greenhouses are a tried and tested method of creating a microclimate suitable for plant production on an annual basis or by extending growing seasons of marginal environments. In Nova Scotia there are over 100 commercial greenhouses, producing plants and vegetables under 186,245 square meters of plastic and glass [1].

Provincial policy in Nova Scotia has resulted in a target to reduce greenhouse gas emissions by at least 10% below 1990 levels by 2020 and a long-term target of 80% below the 2010 level (estimated to be 20.1 Mt) by 2050, which further impacts the greenhouse industry due to its high-energy consumption and GHG emissions [2]. One method of reducing greenhouse gas emissions is by improving energy efficiency using appropriate infrastructural and fuel saving techniques, with the reduction varying depending on the type of fuel used. Another option is the use of alternative fuel sources that have lower GHG emissions. In Nova Scotia, labor is the largest production cost for greenhouse operations, closely followed by energy, which represents 10 to 20 percent of total production costs [3]. Recent rises in fuel prices have further decreased profit margins and put some growers out of business in Nova Scotia. Improving energy efficiency may benefit the grower by reducing annual energy costs and subsequently reducing greenhouse gas emissions.

One step to reduce carbon emissions, ensure energy security and develop a low carbon economy is to replace fossil fuels and other conventional energy sources (such as coal and oil) with renewable resources. In a greenhouse operation, annual heating costs are typically between 70 to 85 percent of the total energy cost [3]. There is therefore a need to identify the most appropriate and sustainable option for heating, herbaceous biomass is potentially one such option for commercial greenhouse operations in Nova Scotia.

Agricultural land in Nova Scotia has decreased by over 73 percent, from 912,000 ha in 1912 to 243,000 ha in 2002 [4]. There is potential therefore for this underutilized land to be used to grow energy crops to economically benefit the grower and prevent productive farmland from turning into forest. Energy crops and residues from agriculture, when properly managed, could sustainably meet a significant portion of farm energy demand. On-farm energy production provides an opportunity to move agricultural activity away from fossil fuel and towards energy that is produced locally with much of the economic returns and cost savings benefiting the producers.

This research reviews the present status of energy use (by components such as boilers, fans and pumps) and operational practices employed by the greenhouse industry in Nova Scotia and identifies potential opportunities to improve energy efficiency and reduce energy consumption, while providing a satisfactory environment for the greenhouse plants. This research investigates alternative biomass fuel options suitable for greenhouse operations in Nova Scotia, and also identifies appropriate biomass processing techniques to improve fuel quality and evaluates biomass boilers and furnaces for emissions (gaseous and particle) and combustion performance.

This thesis comprises of the following chapters:

Chapter 1 – Introduction: Provides an overview of this research.

Chapter 2 – Literature Review: Comprised of a brief review of greenhouse technology and also focuses on biomass feedstock, processing techniques and various biomass fuel and heating system-testing methods.

Chapter 3 – Objectives: Introduces the overall objective and specific objectives of the research project.

Chapter 4 – Materials and Methods: Presents the audit methodology, benchmarking indices, biomass preprocessing techniques, biomass pellet and briquette production along with methods for testing emissions and performance from a biomass combustion system.

Chapter 5 – Statistical Analysis: Deals with statistical design and analysis.

Chapter 6 – Results and Discussions: Reports the consolidated result from energy audits performed along with the results from testing biomass pellets and briquettes on a pilot scale biomass agricultural biomass bioler and a regular woodstove.

Chapter 7 – Conclusions and Recommendations: Summarizes the overall findings and recommendations for future work.

CHAPTER 2 LITERATURE REVIEW

2.1 BACKGROUND

The greenhouse industry in Nova Scotia is actively seeking ways to reduce operation costs, making this industry more sustainable. Heating has been the largest energy expenditure in Nova Scotia greenhouses and using herbaceous biomass for heating could significantly reduce these costs. Identifying the present status of the greenhouse industry in Nova Scotia is essential in improving sustainability. An energy audit is the first step to identify energy use and energy saving opportunities, by providing information on how, when and where energy is being consumed. Information provided by audits could be effectively used to improve efficiency and reduce energy costs and greenhouse gas emissions of any operation.

Many producers also have available land that could be utilized for growing energy crops for combustion on site, however high ash and mineral content in agricultural residues and herbaceous energy crops create challenges during combustion. Increasing environmental restrictions, such as EPA (Environmental Protection Agency) mean that modern biomass boilers are designed to burn feedstocks efficiently with comparatively low emissions. However, the challenges faced with the combustion of herbaceous biomass in existing biomass boilers need to be addressed, one option to achieve this is by improving the fuel quality. The composition of alkali metals and other undesirable compounds vary with different biomass feedstocks. Moreover identical energy crop species have distinct yield and composition at different locations as they are governed by different environmental conditions.

Apart from the locally available agricultural residues, it is imperative to identify methods of developing a sustainable biomass feedstock for combustion. Over wintering is one of the most commonly used techniques to enhance the fuel quality of herbaceous biomass, but this typically results in significant yield loss and requires further investigation [5]. It has reported by a number of researchers that the washing of fuel reduced the total ash content and removed corrosive components from straw [6-9]. Thus improving combustion conditions and fuel quality may improve combustion efficiency and reduce emissions. Densification improves bulk density, ease of handling and combustion quality, however it involves additional costs. Every combustion technology has its own advantages and disadvantages. Choice of different technologies for heating greenhouses depends on a number of factors such as growers' attitude towards a sustainable heating system, initial investment, operating cost and ease of operating the system. Evaluating different stages from the energy crop option through combustion technology is vital in making suggestions and recommendations to the Nova Scotia greenhouse industry.

2.2 GREENHOUSE TECHNOLOGY

The greenhouse industry is one of the most energy-intensive agricultural sectors. Most of the greenhouse energy conservation research dates back to the 1970s and the results of much of this research have been accepted and implemented as standard practices today [10]. The rapid rise in energy costs however has created a renewed interest in this industry and encouraged the evaluation of conservation practices to provide the most cost effective method of maintaining optimum levels of the growth factors - light, heat, humidity and CO_2 concentration [11].

2.2.1 Lighting

Light is an extremely important factor that affects the rate of photosynthesis and influences growth and yield of a plant. Light transmission also affects greenhouse air temperature, humidity and leaf temperature [12]. Total solar radiation received by a greenhouse depends on its structure, orientation and the solar light transmissivity of the glazing. In Nova Scotia, most greenhouses are covered by plastic, with the use of double-glazing encouraged to reduce the winter heat loss [1]. However, double-glazing, condensation and dust are major sources of loss in light transmission [10], with approximately 40% loss reported due to condensation and dust [13]. Condensation also leads to dripping on plants encouraging the incidence of fungal diseases.

A constant endeavor to develop new covering material has provided the greenhouse industry with options to increase light transmission such as anti-drop sheets and cleaning the plastic sheets and providing proper ventilation could significantly improve the light transmission [13]. To improve the light integral in winter month's supplementary lighting is typically employed in floriculture greenhouse operations [14]. Theoretically, the relative photosynthetic yield of High Pressure Sodium (HPS) lamps is 34% higher than that of natural light (due to higher (Photosynthetically Active Radiations) PAR emitted from HPS), with increased concentration of CO_2. Supplementary lighting is believed to provide a high quantity and quality product, but this has an associated cost [15].

2.2.2 Heating

Solar radiation is the predominant source of energy in a greenhouse operation. However, in winter at higher latitudes solar radiation becomes insufficient and additional sources of heating are required [10]. Since, heating is the greatest expenditure of energy in a typical higher latitude cold climate greenhouse operation, saving could be realized by reducing heat loss and using appropriate fuel (such as biomass, natural gas and other low cost fuel) [3]. Improving the thermal insulation and reducing air infiltration using for example double or triple layer glazing has been reported to considerably improve the thermal insulation with savings of 25 to 40% [16], with thermal blankets producing an estimated 40% savings in heating cost [10]. The method of heating affects the greenhouse microclimate. The two most common methods are air and pipe heating. In an air heating system, air is warmer than the leaves in contrast to that of a pipe heating system (where the leaves are warmer than the air due to infrared radiation from the hot pipes). This makes plants more susceptible to fungal diseases [17].

2.2.3 Cooling and Ventilation

During summer and warm winter days, the greenhouse air temperature exceeds the optimum temperature. This warm air needs to be either vented or cooled. Fans are common in many greenhouse ventilation systems, and good maintenance could save 10-20% of fan energy [3]. Evaporative cooling and misting systems are more effective cooling systems than fans and can also cool the air economically [10].

2.2.4 CO_2 Enrichment

Plant synthesizes its own food by reducing carbon dioxide into simple sugar. It is therefore essential to maintain a higher (or) ambient level (340 µmol.mol-1) of carbon dioxide in a greenhouse. Whenever CO_2 consumption by plants is greater than the supply, the concentration is depleted, affecting the photosynthesis rate, thereby reducing greenhouse crop yield. Depletion of 20% or more may be caused by a poor ventilation system [18]. An active ventilation system is highly recommended to maintain the ambient CO_2 concentration in the greenhouse operation, with an increase in CO_2 concentration (700 - 900 µmol.mol-1) creating the potential for improved crop yield. A greenhouse could be enriched with liquefied CO_2 in bulk or through combustion of a clean fuel such as propane or natural gas [19]. Greenhouses are often ventilated in daytime to control temperature and humidity; this makes it uneconomical to maintain CO_2 concentration when it is essential. In practice, most greenhouse growers enrich their operation early morning and late evening, when the ventilation system are turned off [18].

2.3 BIOMASS

The drive to reduce Green House Gas (GHG) emissions and increase renewable energy has created an opportunity for alternative sources of biomass fuel or bioenergy, particularly for residual applications [20, 21]. Biomass is the largest source of renewable energy that contributes about 10.4% of our total primary energy supply [22]. Number of studies suggest biomass to be one of the major contributors for a sustainable global energy supply in future [23].

Wood chips and cordwood are the conventional form of biomass fuel used for heating and cooking. In mid-to-late 1800s, the use of fossil fuels such as coal, oil and natural gas became increasingly popular as it was much energy dense and convenient fuel source than wood [24, 25]. Recent years, awareness on climate change and depleting fossil fuels have brought back wood as a renewable source of energy for domestic heating.

Furthermore, Feed in Tariff (FIT) and other renewable energy policy encourages the use of wood biomass to replace fossil fuels [26, 27]. In the modern world, wood is predominantly used as pellets and chips for applications such as electric power generation, district and domestic heating increasing the demand for wood pellets in developed and developing countries. Globally the use of wood pellets for industrial and residential heating is growing at an average rate of 18% per annum (estimated 6 million tons production capacity in 2006, 50% of which originated from Sweden and North America), with over 15 million tons produced in 2010 [28, 29]. In Canada, there were 33 pellet plants with 2 million tons installed capacity that reportedly produced 1.3 million tons in 2010 [30].

Majority of the wood pellets being produced were sourced for wood waste from sawmills and waste wood (diseased and insect killed trees) form forest [24, 25, 30, 31]. However, expansion of the raw material supply base for the wood pellet industry however will have environmental impacts because the raw materials are either directly or indirectly from forest resources. Depletion of forest resources reduces the carbon reservoir there by reducing the benefits of substituting fossil fuels by bio-energy [32].

At present, there is interest in Nova Scotia for the growth of energy crops, particularly perennial grasses (switch grass, miscanthus, reed canary, etc.) and short rotational coppice (willow, eucalyptus, etc.) [33]. Short rotation coppices (SRC's) provide comparatively a better quality and quantity of biomass feedstock once every 2-4 years; but SRC typically requires more specialized planting and harvesting equipment and larger investment [34]. Whereas, perennial grass could be grown on marginal land and annually harvested with existing farm equipment. Perennial grasses could be a sustainable heating fuel option for greenhouse growers [35]. Using grass biomass as a fuel depends on three important aspects - biomass composition, processing and combustion technology.

2.3.1 Biomass Composition

There are several indicator used to evaluate the quality of a biomass fuel which include calorific value, moisture content, proportion of ash, alkali metals and other undesirable chemical compounds such as chlorine and sulfur. These parameters have a substantial effect on combustion efficiency and if present in sufficient quantities may lead to issues such as ash slagging, clinkering and corrosion of the furnace. The calorific value of biomass typically varies between 15 - 20MJ/kg compared to that of coal (25 - 34 MJ/kg) [36]. Moisture content diminishes the calorific value of the biomass fuel and for every 10% increase in moisture content results in a reduction of calorific value by 2 MJ/kg [37].

Woody biomass typically has a moisture content of 45 - 50%, which requires additional drying before being used as a heating fuel, whereas field dried perennial grass have a moisture content that varies between 12 to 15% [38, 39]. Hence, drying appears to be a major cost component (about 20%) next to the raw materials (as the cost of raw material consistently increases with the price of oil) [40]. However, the fuel quality of wood biomass is better than that of energy grasses. Energy grasses contain 4-6% ash and undesirable alkali metals such as potassium and sodium, which make it unsuitable for burning in existing furnaces. Alkali metals react with the silica in ash producing a molten mass, which blocks the airways in furnace [36]. Further, the alkali metals present in crop residues deposits on the heat exchanger tubes when burnt at higher temperatures (>800 C). These deposits rich in potassium and chlorine corrode the heat exchanger tubes [6, 41]. Overwintering perennial grasses could significantly improve the fuel quality of the feedstock by reducing the potassium and chlorine content but with an accompanying yield loss penalty. It has been reported that the washing of biomass fuel with water significantly reduced potassium, sodium and chloride. Moreover the total ash content was also reduced by about 10% in rice straw and 68% in wheat straw [6]. Experiments were also conducted to remove unwanted components by boiling the straw at temperatures between 50-60 °C [42].

While comparing energy rations of biomass for several wood species and Giant reed, the energy ratios of reed is much higher compared to wood species. For wood species without fertilization energy ratio ranges 10-23 at rotational ages less than 15 years and 42-46 at the rotational ages greater than 30 years [43]. However, for a mature crop of giant reed after establishments without fertilization the energy ration is about 125 [44].

2.3.2 Biomass Densification

Raw biomass has low energy density. Using raw biomass for combustion would be economical only if the source and the utility are located in close proximity. However, biomass can be densified to improve portability and storage. Conventional methods of densification include baling, which can increase its energy density to 2.8 - 3.4 GJ/m^3. Briquetting is another method of densification and can improve energy density to around 6.4 GJ/m^3; alternatively pelletization can results in very high density reaching between

9.8 - 14.0 GJ/m^3. This densification method also improves mass fluidity, which provides more control over boiler feeding thereby improving combustion efficiency and reducing emissions from densified biomass [32].

2.3.3 Emissions from Biomass

Burning biomass is regarded as “Carbon neutral” [45]. Since, most of the carbon in biomass is converted into CO_2, which is taken up by plants during the process of photosynthesis. However, burning biomass under poor combustion conditions, transform a significant portion of the fuel carbon into incomplete combustion products [46]. Furthermore, the presence of alkali metals and other inorganic elements produces other products such as particulates and oxides of nitrogen and sulfur [46]. These products have higher environmental impact and global warming potential compared to CO_2. These factors limit the use of biomass in large district heating units and power plants with multi-pollutant emission control technologies such as scrubbers and ESP’s (Electro Static Precipitators) in place [47, 48].

Particulate matter that evolves through biomass fuel combustion has been associated with various respiratory and cardiovascular issues [49, 50]. The vapors from incomplete combustion and fly ash inorganic materials condense to form particulate matter [51]. The main inorganic components of these particles were potassium, sulfur and chlorine [52, 53]. Apart from particulate matter, burning biomass involves emission of toxic gases such as CO, NO, NO_2 and SO_2. NOx (NO, NO_2 and other oxides of nitrogen) and SOx (SO_2 and other oxides of Sulfur) emission primarily depend on the nitrogen and sulfur content of the fuel [45].

Though properties of the biomass fuels themselves are a vital source of emissions, the condition in which these fuels are combusted is equally important. Numerous studies were conducted and factors that influences efficiency and emission on biomass combustion were presented. Dare et al. performed combustion tests on a small scale 50 kw combustor with bark residue and stem wood of purpose grown eucalyptus and reported that the inorganic reactions highly impacts the combustion behavior of biomass fuel. Further, these reactions are strongly influenced by combustion temperature which in turn is affected by the moisture content of the fuel [54]. Paulrud et al. likewise combusted reed canary grass with different ash content (by blending in leaf and stem fractions) in a 180 kW burner. Results indicated that variation in ash content did not affect the emission from the burner. Furthermore, no severe clinkers or deposits were detected in the burner after combustion [55]. Gonzalez et al. tested a 11.6 kw mural boiler with a range of agricultural biomass residues and reported that both mass flow of fuel and draught greatly affects the combustion efficiency of such boilers [56, 57, 58].

2.3.4 Combustion Technologies

A wide range of furnaces and boilers are available for heating, but are typically not designed to effectively handle the high ash biomass fuels sourced from perennial grasses. Herbaceous biomass has higher contents of nitrogen, chlorine, potassium and sulfur, which lead to increased ash, corrosion and deposits. These issues not only affect the combustion system and its efficiency but also emit gaseous pollutants and particulates to the atmosphere that may have adverse health effects. Emissions from combustion can be categorized into (1) un-burnt pollutants; (2) pollutants due to complete combustion; and (3) particulate emissions.

Adequate mixing of combustion air with the combustible gasses enables high efficiency and high temperature consequently reducing the un-burnt pollutants. Nitrogen in air or the fuel itself at high temperature forms NOx. Air and fuel staging could reduce NOx by up to 50 - 80% on biomass feedstocks. During biomass combustion, salts are formed most of which are due to the presence of potassium. Potassium oxidizes in the presence of oxygen at high temperature, which vaporize to form particles at the gas phase. Hence fuel composition is the main source for particulates formation [59]. Common technologies used direct for the combustion of biomass include i. Wood stove and ii. Pellet stove.

i. Wood log boilers

Traditionally, wood stoves are used for space heating. Although sales of new wood burning appliances have to meeting stricter emission regulations (EPA), many older appliances exist. Combustion in these conventional wood stoves is usually not controlled and it is reported that the particle emissions from such appliances can be up to 50 times higher than that of the controlled combustion stoves [60]. Modern space heating appliances are down draught systems, which is efficient with less emission. Particulate emission of a wood stove could be reduced up to 20 times when it is connected to a heat storage system as it reduces the impact of rapidly varying heat load on to the system [52].

Biomass briquettes could replace wood used in a wood boiler. By using a biomass briquette the combustion efficiency could be significantly improved, as the moisture content would be low compared to wood. However, poor quality fuel will significantly increase the particulates and NOx as it depends on the alkali metal and nitrogen content of the fuel being burnt. In this study, a Drolet XV EPA certified residential wood stove was used for conducting combustion tests on herbaceous biomass briquettes.

ii. Pellet boilers

Compared to the wood boiler the pellet stoves are sophisticated. Modern pellet stoves are equipped with internal fuel storage, automatic fuel feeding and ash removing systems. Moreover, precise control over excess air in pellet stoves have significantly reduced emissions and improved combustion efficiency [61]. Although pellet boilers are superior in burning biomass at higher efficiency, these boilers are expensive and their operation involves a number of electrical and mechanical components that requires routine maintenance.

Recent years, pellet boilers are specially build to burn herbaceous biomass with higher ash content. One such boiler specially designed by LST Energy inc. is being used for this study.

A range of combustion studies have been conducted with a numerous herbaceous and agricultural residue pellets. Verma et al. combusted six biomass pellets in a 40 kW pellet boiler and compared the difference in emission and efficiency when fired at nominal and reduced load [62]. Verma et al. in his other experiment tested a multi fuel pellet boiler under standard laboratory conditions and two other DIN certified boiler in real life conditions with eight different biomass boiler. He reported higher NOx emissions and lower Co and dust emission in real life condition compared to standard laboratory conditions. Moreover, straw pellets with high ash content and lower ash melting point was reported less suitable pellets for combustion in standard laboratory condition [63].

Liu et al. investigated the effect of mixing bamboo and rice straw on pellet property. As a result of his investigation, they proved mixing different biomass materials is an effective way to optimize fuel properties [64]. Holt et al. fabricated pellets from cotton gin byproducts and evaluated the gaseous and particulate emissions derived from the fabricated pellet in a commercially available pellet stove. The purpose of this experiment was to turn cotton gin by products into a useful commodity [65].

CHAPTER 3 OBJECTIVES

The overall objective of this research is to identify energy use in the greenhouse industry and suggest appropriate energy management opportunities which will facilitate energy cost reduction in the Nova Scotia greenhouse industry. The following are the specific objectives of this research,

- To review the present status of the greenhouse industry via energy audits on selected greenhouses in Nova Scotia and create an energy use inventory to identify appropriate energy management opportunities based on information collected through energy audits.
- To investigate the potential of using herbaceous biomass to replace wood biomass by conducting emissions and combustion performance tests.
- To identify appropriate preprocessing techniques to improve the fuel properties of herbaceous biomass.
- To perform a comparative emissions and combustion performance test on preprocessed and raw herbaceous biomass feedstocks to investigate the impacts of preprocessing on the fuel characteristics and thereby to expand on the potential to reduce emissions and improved combustion performance.

CHAPTER 4 MATERIALS AND METHODS

Greenhouse operations are energy intensive production system compared to many other agricultural sectors [66]. Greenhouses in NS predominantly use energy in the form of heat (using fuels such as fuel oil and wood) and electricity (for all other purposes such as lighting, cooling and ventilation). The choice of fuel sources is limited in NS, compared to the rest of Canada, making the industry susceptible to changes in energy prices. Increasing prices of fuel and electricity still continue to be a major challenge.

4.1 GREENHOUSE INVENTORY AND ENERGY COST BREAKDOWN

In this study, to review the status of the greenhouses industry in Nova Scotia 10 greenhouses (members of Greenhouse Nova Scotia (GNS)) were selected and all agreed to participate in the study. Information was obtained including greenhouse infrastructure, lighting, heating, cooling, ventilation, CO_2 enrichment and irrigation. The inventory data would be a pre-audit assessment of greenhouses. The inventory will also be a source to choose greenhouses on which detailed audits will be conducted. The greenhouses were chosen based on diversity in-terms of their infrastructure, size, product and location.

4.1.1 Energy Audit Methodology

Energy audits are performed on greenhouses operation at three levels. These levels were chosen based on the information and time available with the greenhouse operators.

i. Walk-through (level 1 Audit)

In walk through audits, as the name indicates, each and every energy component of the operation is visually inspected. However, these audits are usually not sufficient enough to recommend Energy Efficiency Measures (EEM's). Measures that may improve the efficiency of a component are suggested and a rough payback period is given to the operators. Most of the suggestion may include the cost associated with them.

ii. Energy Cost Breakdown and Cost Savings Analysis (Level 2 Audit)

This includes the analysis of the utility bills and comparison with estimated energy use and operation hours. The energy use can be broken-down into different categories. From the energy use breakdown, the EEM can be chosen and the potential savings that can be realized or the payback period are reported.

For Example,

i. A circulation pump runs continuously even under minimal load – A frequency control drive would be suggested and the payback period will be calculated and reported.

ii. Use of incandescent lamps – Fluorescent (T5 or T8) or Compact Fluorescent Lamp's (CFL's) will be recommended based on the lumens required. Further, the payback period and potential saving after the payback period will be calculated and presented in the report.

iii. Energy Monitoring Devices and Detailed Analysis (Level 3 Audit)

Detailed audits involve installing energy monitoring devices such as WELServer or HOBO systems that can record power (or) energy consumption over a period of time. The detailed energy audits do involve in minimal assumptions; the suggestions and payback period would be precise. Further, it involves in demand and creating energy profiles for various equipment.

For Example,

i. Load shifting – Greenhouse operations billed under rate class commercial and industrial category are charged for maximum demand apart from total energy consumption. A demand profile is used for reducing the maximum demand of a greenhouse operation. Peak demand from the profile is identified and the loads turn on during peak demand will be identified and all possible chance of distributing the load will be identified.

ii. Running a system at maximum efficiency – systems that are using electric motors can be monitored and form the energy profile of the system load at which the system operates at maximum efficiency can be identified and then the operator would be advised to operate the system around that specific load to maximize system efficiency.

4.1.2 Benchmarking Indices

Benchmarking is an effective tool to compare two or more greenhouse operations in terms of their energy consumption. Energy Utilization Index (EUI) and Energy Cost Index (ECI) are two important ratios that are typically used.

i. Energy Utilization Index (EUI)

Energy Utilization index (or) Energy Use Index is a measure of the total energy consumed annually by a greenhouse operation divided by the total physical operational area of the greenhouse. EUI can be either represented in MBTU's/ft^2 (or) MJ / m^2 and can be calculated for the utility bills, where the total oil (in liters) or Electricity (in kWhr) can be converted into (MJ) and presented in (MJ / m^2).

ii. Energy Cost Index (ECI)

Energy Cost index (ECI) or Cost Index is an alternative method of comparing energy consumption and is a measure of total operational expense ($) per square meter of greenhouse area, represented in ($/m^2).

4.1.3 Energy Cost Breakdown

To assess appropriate energy management opportunities it is essential to know where, when and how energy is being consumed. Energy use inventory is an effective tool that provides information on how the total energy from the mains is distributed to various loads in a greenhouse operation.

4.1.4 Energy Monitoring System

One of the ten-selected greenhouse operations was monitored for the entire season to better understand the energy demand and consumption. WEL or HOBO monitoring system were installed to monitor temperature and humidity in greenhouses and power, current and on/off time of various greenhouse components. WEL (Web Energy Logger) is a one-wire network remote monitoring device developed by Maxim, which enables a large number of sensors to be attached to a pair of twisted cables. Further, WEL server posts data the Internet. Real time data can be observed online and data collected over a long period of time can be downloaded as .csv file. HOBO offers a range of monitoring devices such as current, air temperature, relative humidity, light intensity and many more parameters. Unlike WEL servers, data from the sensors are stored on a data logger on site. Data from the loggers were collected at regular intervals on site.

4.2 BIOMASS FEEDSTOCKS USED IN THIS EXPERIMENT

Four feedstock chosen for this study were reed canary grass, switch grass, wheat and barley straw. Where reed canary and switch grass represents energy crops that has a potential to be grown in Nova Scotia and wheat and barley straw represents commonly available agricultural residues in Nova Scotia. Reed canary grass (*Phalaris arundinacea*) was collected as a 700 lbs. round bale from a dairy farm near Truro, NS (+45° 22’ 46.3”, -63° 27’ 38.6”). Switch grass (*Panicum varigatum*) was bought as a 50 lbs. (22.68 kg) square bale from a commercial energy crop grower located in Antigonish, NS (+45° 33’ 40.6”, -61° 51’ 9.6”). Wheat (*Triticum spp.*) and Barley (*Hordeum vulgare*) were collected as 400 lbs. (181.44 kg) round bales from the farm plots of Dalhousie University, Agriculture Campus in Truro, NS (+45° 22’ 23.2”, -63° 15’ 17.2”).

4.3 FEEDSTOCK PRE-PROCESSING

The feedstock collected as bales were first pre-ground in a Supreme Enviro pull type TMR (Total Mixed Ration – Figure 1) mixer to reduce the whole bale to stalk of about 3 – 6 inches (7.5 – 15 cm) in lengths.

Figure 1. Feedstock preprocessed in a Supreme Enviro pull type TMR mixer.

Figure 2. Chopped feedstock fed into New Holland hammer mill to reduce feedstocks into fine fibers.

Chopped straw was fed into New Holland hammer mill (Figure 2) with a ¼ inch (6.35 mm) screen to reduce the feedstock to a fine fiber (1 – 2 mm in width and 1-1.5 cm in length). Hammer milled feedstock were used for hot water leaching, pellets and briquettes combustion experiments.

4.4 PELLET COMBUSTION EXPERIMENT

There were two objectives to this experiment, the first is to produce pellets using switch and reed canary grass (representing energy crops) and wheat and barley straw (representing agricultural residue) that are available in Nova Scotia. The second objective is to evaluate gaseous and particulate emissions from the pellets produced from each of these feedstock and compare with a premium grade wood pellet in a pilot scale agro-pellet stove specially designed by LST Energy Inc. (Figure 5).

4.4.1 Pellet Production

Pellets were produced in a small scale LM72A pellet mill designed by Lawson Mills Biomass Solutions Ltd, Prince Edward Island, Canada. The LM72A mill is capable of producing up to 350 lbs. (158 kg) of pellets per hour. The feedstock were received as bales and initially chopped in a Total Ratio Mixer and transferred to a New Holland hammer mill with ¼ inch (6.35 mm) screen to reduce the chopped stalks into fine fibers suitable for making pellets. The LM72A pellet mill has three sections (Figure 3):

i. In Feed Zone

The in feed zone consists of two hoppers. The first hopper called the main or feedstock hopper contains the primary feedstock for making pellets. The second hopper called the auxiliary hopper was designed to contain binders (however, binders were not used in the experiment), both hoppers have an anti-bridging system. However, the feed stock hopper contains a screw auger but the auxiliary hopper consists of a flux auger for delivering binders at low volume. Both augers drop contents into a mixing arm the blends the feedstock, binder and water from a reciprocating pump. The reciprocating pump can be adjusted to control the moisture content of the feedstock.

Figure 3. LM72A – Pellet Mill, Lawson Mills Biomass Solutions, Prince Edward Island.

ii. Milling Zone

Feed stock from the in feed zone flows in the pellet mill that consists of a flat die with a roller assembly on top. The flat die powered by a 7-horse power motor rotated and the roller pushes the feedstock through the holes in the die, where a bottom mounted metal knife cuts the pellets at desired length.

Figure 4. Pellets (bottom row) and hammer milled feedstock (bottom row) from which pellets were produced. (Left to right) Barley straw, Reed canary grass, Switch Grass and Wheat straw.

iii. Cooling and Packing zone

Pellets formed in the milling zone drop into the cooling chamber that consists of an inclined drum with numerous holes to reduce fines in the pellets. The fines are cast back into the hopper and the pellets with minimum or no fines are passed onto a conveyor that bags the pellets. Figure 4, top row, displays an example of material, post hammer mill for each feedstock, with the resultant pellets produced by the LM72A in the lower row.

4.4.2 Agro Pellet Boiler

The LST pilot scale agro-pellet boiler is a 32 kW manually fired boiler with a specially designed burn-pot to handle clinker from high ash content fuels. It consists of a hopper that can hold up to 140 kg of pellets. Below the hopper there is an inclined screw auger controlled by a variable frequency drive, which can vary the feed rate from 0 to 3 kg per hour. Pellets from the hopper pass through the auger and drop into a burn pot, (20 cm in diameter) which has a motor driven agitator that turns at a constant speed of 6 rpm to remove clinkers which may form during combustion. The burn pot also has numerous holes (8 mm diameter) that allow air to flow from the combustion fan.

The hot flue gas from the burn pot passes through a boiler that has 6 vertical fire exchanger tubes that transfer heat from the flue gas to the water that is circulated by the pump through the unit heaters. The flue gas exits from the boiler to the chimney through an induced draught fan. Below the burn-pot an ash receiver receives ash during combustion, which is then augured into an ash pot at regular intervals.

4.4.3 Experimental Design

i. Feed Auger Calibration

The feed auger was initially calibrated to feed 2500 kg/hour, based on the size and density of the pellets. Auger calibration was achieved by weighing pellets fed from the hopper to a collection bin. The hopper was filled with one of five different pellets (4 grass and 1 wood) and the auger set at 30, 40, 50, 60 and 70% feed rate using the frequency control drive.

The pellets were collected for 30 minutes at the end of the auger and weighed. This experiment was replicated three times at each feed rate for each pellet and the averaged weight was recorded.

At the end of the experiment, regression analysis was used to relate the independent variable (feed rate, in %) with the dependent variable (weight, in Kg). Since the relationship was linear, a first order polynomial equation (1) was used to represent their relationship. The feed rates of five different pellets were identified from five different linear regression equations.

$$y = mx + c \text{ ----- } (1)$$

ii. Starting the boiler

The boiler was started by adding 500 grams of premium wood pellets into the burn pot and igniting it with a propane burner for about two minutes. The feed auger was turned on and set to the desired feed rate. After fifteen minutes, both combustion and induced draught fan were turned on and the speed set to appropriate levels.

The circulation pump was turned on as soon as the temperature and pressure of the boiler reached 80 °C and 15 psi (103 kPa) respectively. After the agitator was turned on, temperature of the flue gas began to fluctuate. Overtime the boiler reached a steady temperature (±10 K) considered the steady state operating condition. The gaseous and particulates emission were measured at steady state conditions as per the methodology described below.

Figure 5. Agro-Pellet Boiler designed by LST Energy Inc., Pictou County, Nova Scotia.

4.4.4 Gaseous emissions measurement Methodology

The flue gas from the pellet boiler was sampled continuously at one minute time intervals using a Eurotron Unigas 3000+ flue gas analyzer (Figure 6) with a probe that consisted of a filter and water trap. The flue gas analyzer has four electrochemical cells/sensors that can measure oxygen, carbon monoxide, sulfur dioxide and nitrous oxide concentrations.

Figure 6. Eurotron Unigas 3000+ flue gas analyzer installed in the Exhaust of the Agro -pellet boiler.

From these measurements the carbon dioxide, oxides of nitrogen and excess air concentration along with the efficiency were calculated using the indirect method [31].

Apart from the electrochemical cells there was also a type – K thermocouple that measured the flue gas temperature. The probe was connected before the induced draught fan and flue gas was sampled every minute. The gaseous values were normalized to volumetric oxygen content of 13% ($O_{2\,ref}$) in the exhaust gas. The values were normalized using equation (2).

$$X_{norm} = X_{meas} \cdot (21 - O_{2\,ref})/(21 - O_{2\,meas}) \quad \text{-------} \ (2)$$

Where,

X_{norm} – normalized emission value (ppm)

X_{meas} – measured emission value (ppm)

$O_{2\,ref}$ – reference oxygen concentration (%)

$O_{2\,meas}$ – measured oxygen concentration (%)

4.4.5 Particulate emissions measurement Methodology

The particulate matter analyzer had a heated sampling train that consisted of a heated stainless steel probe with a nozzle towards the stack end and a pitot tube to measure the velocity (i.e. the velocity pressure) of the flue gas. The other end of the probe was connected to a heated glass filter chamber, where a fiberglass filter was placed to capture the particulates (Total Suspended Particulates – TSP) from the flue gas. The flue gas from the filtered chamber passed through a series of impinges with water and silica gel to capture water from the flue gas.

The particulate emissions were measured using a Clean Air EPA Method 5 Particulate Matter Analyzer (Figure 7).

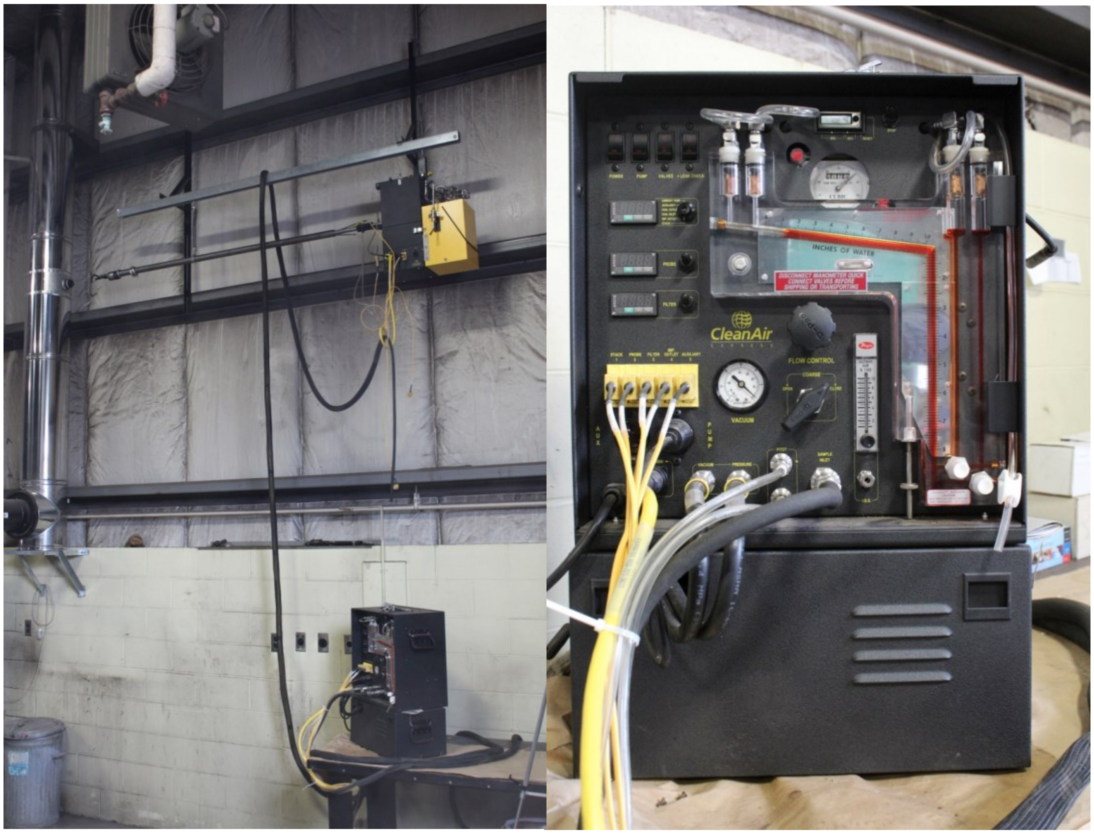


Figure 7. Sampling train (Left) and Control Console (Right) of Clean Air EPA Method 5 Particulate matter analyzer.

An umbilical cord connected between the sampling train and the control console which had a Dry Gas Meter (DGM), manometer, vacuum pump and valves along with other control units to isokinetically (to sample the flue gas exactly at the same velocity as the flue gas velocity) sample the flue gas.

4.5 HOT WATER LEACHING EXPERIMENT

Leaching experiments were designed to investigate the potential impact of water temperature and residence time in controlled batch leaching or washing of agricultural biomass. Two (2) different residence times and three (3) different water temperatures were selected as experimental variables, to yield six (6) experiments per feedstock for a total of 24 experiments and each experiment was replicated three times.

In order to obtain a homogeneous sample, for each of the four raw feedstock, the following process was used. Each feedstock was milled separately using a New Holland 358 hammer mill fitted with a ¼ inch (6.35 mm) screen. A few hundred grams of each feedstock was dried in a Fisher Scientific - isotemp programmable muffle furnace at 105°C for 24 hours.

Fifteen (15) grams of each oven-dried feedstock sample was then added to one (1) liter of millipore water in a hot water bath, which was heated to the three experimental temperatures of 20^{o}C, 50^{o}C and 80^{o}C. The temperature was maintained using a Julabo refrigerated and heating circulator. The feedstock samples were manually agitated for five (5) minutes and a circular steel mesh pushed through the top of the beaker to submerge the sample thoroughly in the water. Samples of each feedstock were taken after the two experimental residence times of 6 hours and 24 hours and filtered through Whatmann 2 filter paper. The filter samples were oven-dried again at 105°C for 24 hours.

4.6 BRIQUETTE COMBUSTION EXPERIMENT

4.6.1 Leaching (washing)

A one thousand liter custom-built aluminum tank with a filter and bottom drain was used for leaching these experimental feedstocks. The aluminum tank was filled with 600 liters of well water (at temperature 18±3°C) and 8 kg of feedstock. The tank was manually agitated for 10 minutes with a wooden paddle, so that the entire feedstock was soaked in water. After 24 hours, the feedstock was agitated again with a wooden paddle for 10 minutes and the water was released using the tap with filter. All four feedstock were spread in a greenhouse and air-dried (for one month). As the moisture content of the feedstock reached about 15%, they were bagged for processing into briquettes.

4.6.2 Briquetting

The leached and un-leached feedstocks were converted into 50 mm (diameter) briquettes using a Weima C 150 Briquette press. Figure 8 shows the front view of Wiema C 150 briquette machine. The Weima C 150 is a simple PLC (Programmable Logic Control) controlled hydraulic briquette machine.

The briquette machine has a hopper set up with an agitator and a worm which augers feedstock into the pressing chamber. An integrated hydraulic system compresses the feedstock at pressures of up to 2600 psi applied through the piston.

Figure 8. Front View of Wiema C 150 briquette machine.

The briquettes produced from the leached and un-leached biomass are shown in Figures 9 and 10. The Weima C 150 can process 50 kg of standard saw dust every hour reducing the volume to 10:1 ratio. This process resulted in volume reductions of up to 70% for wheat and barley straw and 60% for reed canary and switch grass.

Figure 9. Grass briquettes (bottom row) made from un-leached and leached biomass feedstock (top row). Left to right: Unleached reed canary grass; Leached reed canary grass; Unleached switch grass; Leached switch grass.

Figure 10. Straw briquettes (bottom row) made from un-leached and leached biomass feedstock (top row). Left to right: Unleached wheat straw; Leached wheat straw; Unleached Barley straw; Leached barley straw.

4.6.3 Experiment Design

In total, eight different briquettes for were produced for the combustion tests. The combustion tests were replicated three times for each of the eight briquettes using 2 kg of sample for each test.

Figure 11. Drolet XV Stove with ambers from wood before introducing biomass briquettes.

As an initial phase of the experimental design, the biomass briquettes were trial tested under standard experimental conditions to identify possible design flaws and difficulties that may arise during the combustion experiment. Few modifications were necessary, due to the fact that all four biomass briquettes failed to ignite in spite of excess starters. Hence, the experiment was started by igniting a wood log (1kg ± 50g). As the wood log burned into ambers without flames, they were evenly distributed in the combustion chamber (Figure 11) and the briquette samples then introduced.

The briquettes smoked with flames evident in less than one minute of being placed in the combustion chamber with complete combustion of the briquettes occurring in around one hour. The flue gas was sampled every minute for gaseous emissions immediately following briquette ignition with a Eurotron Unigas 3000+ flue gas analyzer. In addition, when the burn reached steady state the flue gas was sampled isokineticlly for particulates with a Clean Air method 5 sampling train.

4.7 ANALYTICAL METHODS

The leached and unleached feedstock were oven-dried and ground in a mini-wily mill with a 40 mesh. Ultimate, proximate analysis and elemental analysis was performed on the ground samples.

i. Ultimate Analysis (for Combustion Experiment)

Ultimate analysis (Carbon, Hydrogen, Nitrogen, Sulfur and Oxygen) was performed in Canadian BioEnergy Centre, UNB, New Brunswick, Canada. Carbon and Hydrogen was found as a gaseous product on complete combustion using standard test method ASTM E777. Sulfur (ASTM E775) and Nitrogen (ASTM E778) were found as a whole and Oxygen was calculated by difference (100 – (C + H + N + S)).

ii. Proximate Analysis (for Combustion Experiment)

Proximate analysis was carried out with a Fisher Scientific isotemp programmable muffle furnace to determine the moisture content (ASTM E871), volatile matter (ASTM E872), ash content (ASTM D1102) and fixed carbon (by difference). Moisture content was represented as a loss in ignition over 24 hours at 105 ^{o}C. For volatile matter, a gram of the sample was placed in a porcelain dish and placed in a muffle furnace at 600 ^{o}C for 10 minutes. Volatile matter on a dry basis was represented as a percentage loss in weight to oven-dried weight of the sample. Further, ash content on a dry basis was expressed as percentage loss in weight when ignited at 600 ^{o}C for 6 hours to the weight of the oven dried sample. Fixed carbon on a dry basis was calculated by subtracting volatile matter and ash from 100%.

iii. Energy Content (Higher Heating Value – for Combustion Experiment)

Parr oxygen bomb calorimeter was used to determine the heating value of the sample. Approximately one gram of sample was placed in the bomb and pressurized with oxygen to 30 atm. After which, the bomb was placed in an insulated beaker containing 2 liters of water. Later, the sample was ignited with a fuse wired to the ignition unit and the rise in temperature was noted and using standard formulae the heating value was calculated (ASTM E-711 (2004)).

iv. Alkali Metals (K, Ca, Na, Mg – for Leaching Experiment)

Atomic Absorption Spectroscopy was performed using a Varian SpectrAA 200FS to analyze Potassium (K), Calcium (Ca), Sodium (Na) and Magnesium (Mg). One (1) gram of each feedstock was placed in a porcelain dish and preheated in an electric furnace for approximately 20 minutes. After which the samples were ignited in a muffle furnace at 550°C for at least 6 hours. The ash samples were allowed to cool in a desiccator for at least one (1) hour and 10ml of 5% HCl added to the dishes. Ten (10) minutes later the dishes were rinsed into a 50 ml volumetric flask through a Whatmann 1 filter in a conical funnel. The extracted feedstock samples were then analyzed for alkali metals with the concentration represented in mg/g.

v. Total Nitrogen and Sulfur (for Leaching Experiment)

LECO – 3000 CNS was used to analyze total nitrogen and sulfur, approximately 0.2 grams of each feedstock sample was placed in tin foil, wrapped and loaded in the auto-sampler. The sampler was loaded initially with three blanks and three standards. Additionally, a standard was loaded with a blank every tenth sample.

vi. Total Chlorine

ASTM D4208-13 (Standard Test Method for Total Chlorine in Coal by the Oxygen Bomb Combustion/Ion Selective Electrode Method) was used to analyze total chlorine for each feedstock sample. Total chlorine content in the sample was presented in ppm.

CHAPTER 5 STATISTICAL ANALYSIS

All statistical analysis was carried out in Minitab 16 (Minitab Inc., State College, PA, USA) and SAS 9.3 (SAS Institute Inc., NC, USA).

5.1 EMISSIONS AND COMBUSTION PERFORMANCE OF AGRO-PELLETS AGAINST PREMIUM WOOD PELLETS

5.1.1 Feed Auger Calibration

The feed auger was calibrated using simple linear regression to feed five pellets of different size and density at a uniform rate of 2500 grams/hour. The hopper was filled with one of five different pellets (4 grass and 1 wood) and the auger set at 30, 40, 50, 60 and 70% feed rate using the frequency control drive. The pellets were collected at the end of the feed auger and weighed to get the values of the dependent variable.

i. Pearson's Correlation (r)

Pearson's correlation is a statistical measure that indicates the relation between the dependent and independent variable. Pearson's correlation statistic ranges between -1 and +1. Where, ± 1 to ±0.7 indicates a strong relation; ± 0.7 to ± 0.3 indicates week relation; ± 0.3 to 0 indicates no relation. Using Pearson's correlation the relation between dependent (Weight in grams) and independent variable (Feed rate in percentage) could be found.

ii. Simple Linear Regression

Simple linear Regression is a form of statistical modeling that attempts to evaluate the relationship between the dependent variable and the independent variable through a single equation. Equation (3) describes the regression line, which determines how dependent variable (Y) changes as the independent variable (X) changes. The fitted model is given by,

$$Y = b_0 + b_1X + \varepsilon \text{ ------ } (3)$$

Where,

b_1 = slope ($\Delta Y/\Delta X$);

b_0 = y-intercept, the value of y when $x = 0$;

ε = error term;

5.1.2 Gaseous and Particulate Matter Emissions

There are five feedstocks (premium wood pellets + 4 agro pellets) to compare. Whenever there are more than two groups of data to compare, ANOVA (ANalysis Of VAriance) should be used.

i. Completely Randomized Design (CRD)

In this experiment, there is only one factor of interest (feedstocks). Hence one-way ANOVA (Proc glm) with CRD model was used to analyze this experiment. The model (4) used to analyze is given by,

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij} \text{ ----- } (4)$$

Where, Y_{ij} is the response (CO, NOx, Sox, TSP) for the i^{th} ($i=1\ldots4$) factor and j^{th} ($j=1\ldots4$) replicate, μ is the population mean for the response, τ_i is the factor effect for the i^{th} factor, and ε_{ij} is the error terms for the i^{th} factor and j^{th} replicate.

Hypothesis:

$Ho: \tau_1 = \tau_2 = \tau_3 = \tau_4 = \tau_5 = 0$

Ha: at least $\tau \neq 0$

ii. Multiple Means Comparison (LSD)

ANOVA provides information on whether or not at least one mean is significantly different from the other. If H_0 is rejected, multiple means comparison has to be performed that look at the individual means of each treatment and compare them statistically so that we can choose the best treatment. There are several tests for running these kinds of comparisons, however Tukeys and LSD are the tests that are predominantly used.

As a rule of thumb, if experimental error is high then LSD is used. It is easier to reject the null with this test. If experimental error is low then Tukeys is used. With this test it is harder to reject the null.

Multiple means comparison is done in SAS using following statement after the model statement,

MEANS “FACTOR” / TUKEY; (or LSD)

In the output the means are listed in descending order and each mean is represented with one or more letters. The factors can be grouped into various groups using the alphabets. Groups with the same letter are not statistically different from one another. Groups with different letters are statistically different at the specified level of significance.

SAS Statements,

```
PROC GLM;
CLASS “FACTOR”;
MODEL “RESPONSE” = “FACTOR”;
MEANS “FACTOR” / TUKEY;
RUN;
```

5.2 CONTROLLED BATCH LEACHING CONDITIONS FOR OPTIMAL UPGRADING OF AGRICULTURAL BIOMASS

The influence of residence time and water temperature was assessed separately for each feedstock using analysis of variance (ANOVA) in a 2x3 full factorial design. Since the analysis contains two factors and one of those factors is time, repeated statement in MIXED procedure of SAS 9.3 (SAS Institute Inc.) was implemented. The following model (5) was used for analysis,

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ijk} \text{ ------ } (5)$$

Where,

μ = overall mean; α_i = effect of temperature factor; β_j = effect of time factor; $\alpha\beta_{ij}$ = interaction effect of temperature and time factor; ε_{ijk} = overall experimental error.

Hypothesis:

In addition to the main effects, there is also a two-way interaction effect; Hypothesis for various treatment effects can be written as

Main effects:

Ho: $\alpha_1 = \alpha_2 = 0$ H$_o$: $\beta_1 = \beta_2 = \beta_3 = 0$

Ha: At least one $\alpha \neq 0$ Ha: At least one of the $\beta \neq 0$

Two-way interactions:

Ho: Every $\alpha\beta_{ij} = 0$

Ha: Atleast one $\alpha\beta_{ij} \neq 0$

When the ANOVA results are significant (if P-value is less than 0.05(α)) for the interaction effect, Tukey's test (α=0.05) (explained in section 5.1.2 (ii)) was used to compare the means for different resident time and water temperature combinations. If and only if, the interaction is not significant the significance of the main effect is considered for means comparison.

Multiple means comparison is done in SAS using following statement after the model statement (Since in a factorial design interaction of two or more factors are involved),

LSMEANS "FACTOR" / TUKEY; (or LSD)

SAS Statements:

```
PROC MIXED;
CLASS “FACTOR 1” “FACTOR 2”
MODEL “RESPONSES” = FACTOR 1| FACTOR 2;
LSMEANS “FACTORs” / TUKEY;
RUN;
```

5.3 Comparison of Gaseous and Particle Emissions from Leached and Un-leached biomass briquettes in a Domestic Wood Stove

i. Full Factorial Design (2 × 4)

The data for flue gas parameters and TSP of different biomass briquettes were analyzed with the PROC MIXED procedure of SAS version 9.3 (SAS Institute Inc., 2013; USA). The combustion tests were replicated three times for each of the eight briquettes using 2 kg of sample for each test. The experiment was analyzed as a 2x4 full factorial design with two levels of the factor leaching (leached and unleached) and four levels of factor feedstocks (reed, switch, wheat and barley) using a the statistical model (6) that is represented as,

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ijk} \text{ ----- } (6)$$

Where, Y_{ij} is the response variable; μ is the overall mean; α_i is the effect leached or unleached briquettes; βj is the effect of jth feedstock; ε_{ij} is the random error associated

Y_{ij}. Contrasts and Tukeys multiple means comparison were used if there was a significant factor effects at $P < 0.05$(level of significance).

Hypothesis:

Main effects:

Ho: $\alpha_1 = \alpha_2 = 0$ H_o: $\beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$

Ha: At least one $\alpha \neq 0$ Ha: At least one of the $\beta \neq 0$

Two-way interactions:

Ho: Every $\alpha\beta_{ij} = 0$

Ha: Atleast one $\alpha\beta_{ij} \neq 0$

When the ANOVA results are significant (if P-value is less than 0.05(α)) for the interaction effect, Tukey's test (α=0.05) (explained in section 5.1.2 (ii)) was used to compare the means for different resident time and water temperature combinations. If and only if, the interaction is not significant the significance of the main effect is considered for means comparison.

Adequacy of the model, Pearson's correlation between the dependent (a. oxides of nitrogen; b. oxides of sulfur; c. total suspended particulates) and independent (a. nitrogen; b. sulfur; c. ash, chlorine and potassium) variable was determined using Minitab 16, (Minitab Inc., 2013; USA). Regression was performed, if a strong correlation was found between independent and the dependent variables (explained in section 5.1).

ii. Contrast

In addition to Tukeys, Contrast statement in SAS was used to compare the mean of one group with the mean of other group. In this analysis this statement was used to compare leached and unleached briquettes. The following statement was used next to the model statement to compare the groups. SAS statements are similar to statements in section 5.2.

```
CONTRAST ‘Leached vs Unleached’ “FACTOR” -1 -1 -1 -1 1 1 1 1;
```

CHAPTER 6 RESULTS AND DISCUSSION

(Part of this chapter was published in the Journal of Sustainable Bioenergy Systems; P. Ravichandran, D. Gibb and K. Corscadden, "Controlled Batch Leaching Conditions for Optimal Upgrading of Agricultural Biomass," Journal of Sustainable Bioenergy Systems, Vol. 3 No. 3, 2013, pp. 186-193.)

6.1 GREENHOUSE INVENTORY

General information (such as greenhouse size, months of operation, infrastructure, lighting, heating, CO2 injection, irrigation, cooling and ventilation) collected during initial visits are tabulated and presented in Appendix A as inventory data.

6.2 BENCHMARKING GREENHOUSE OPERATIONS

Five of the ten selected operations agreed to share their utility bills from power, fuel oil, propane and pellet distribution companies. Utility bills from the year 2011 were used to calculate the Energy Utilization Index and Energy Cost Index.

6.2.1 Energy Utilization Index (EUI)

Overall energy consumption as electricity (in kWhr), fuel oil and propane (in liters) and pellets (in tons) in the year 2011 were converted to Mega Joules and divided by the total operational area of the greenhouse operation to obtain EUI.

However, there is a disadvantage of using EUI to compare a greenhouse that operates year around and one that operates for only three months of the year. Furthermore, in greenhouse operations it is not unusual to use a few greenhouses in winter during the starting phase and gradually increase space utilization. Hence, EUI is an effective tool to compare energy consumption among greenhouse operations that operate over the same period of time in a year and have a similar space utilization strategy, although this could be pro-rated.

6.2.2 Energy Cost Index (ECI)

Annual Energy Cost spent on electricity, fuel oil, propane and pellets in dollars (Canadian) divided by total operational area in square meter represents ECI.

Table 1 below presents the Energy Utilization Index and Energy Cost Index of 5 of the 10 greenhouses audited for this study.

	EUI, MJ/m^2	**ECI, \$/m^2**
Greenhouse 4	14.94	1.12
Greenhouse 5	21.82	1.46
Greenhouse 6	23.24	8.12
Greenhouse 7	27.08	0.86
Greenhouse 8	19.25	1.49

Table 1. EUI and ECI for commercial greenhouse operations 4,5,6,7 and 8.

Similar to EUI, ECI also has certain challenges when comparing greenhouses with different operation periods in one operating year and space utilization strategies. In addition, the ECI also has a disadvantage when comparing greenhouses that use different fuel. For example, one operation may use wood pellets as a fuel and another may use fuel oil #2. Cost of providing heat will therefore vary along with the current costs of the provided fuel, which may mask improvements in efficiency.

6.3 ENERGY COST BREAKDOWN

An inventory of the energy using components of each operation were gathered, from machine labels on the plates and the approximate time of use obtained from the operators. The information was compiled in a spreadsheet and accuracy of the information was verified by comparison with utility bills. Energy use was broken down into the following categories, lighting, heating, irrigation, cooling/ventilation and others (that may include components such as soil mixers, computers, coolers etc). The section below will analyze and discuss each of the categories based on the commercial greenhouses visited for this study. The Energy cost breakdown for five of ten selected greenhouse is given in Appendix B.

6.3.1 Lighting

Light is an important factor that contributes to photosynthesis and supplementary lighting is a proven technology, which improves yield. It is estimated that the the total energy is used for lighting in greenhouses in Nova Scotia varies between 2 to 21%. Lighting is typically achieved with fluorescent lamps and Compact Fluorescent Lamps

(CFLs), with over 70% of the greenhouse operations using high discharge sodium lamps as supplementary lighting in nurseries to start vegetables and ornamental plants. However, these supplementary lights are only used for a maximum of one or two months (January and/or February). As an exception, Greenhouse 6 uses supplementary lighting year round only for the cut flower production operation of about 100,000 square feet.

There were a few greenhouse operations that used incandescent lamps; suggestions were made to replace them with CFL's. Operations using fluorescent lamps (40 W, T10) were recommended to use T8's and T5's instead. Payback periods for these replacements ranged from 2 to 5 years.

6.3.2 Ventilation and Cooling

A significant amount of electrical energy is used for circulation fans and pumps to evenly distribute heat in the greenhouses in winter and for exhaust and circulation fans to cool the greenhouses in summer. Overall, energy spent for ventilation and cooling ranged from 7 to 15 % of the total energy consumed. All of the gutter-connected greenhouses examined in this research used exhaust and circulation fans along with ridge ventilation. However, most of the freestanding greenhouses depend only on fans for ventilation. Greenhouse 1 was the only operation with side wall rollups and ridge ventilation and the exhaust fans were only used during emergency conditions.

Greenhouse 10 had a retractable roof, where the entire double poly roof slides to enclose the structure under cold weather and opens the structure under normal weather conditions. The larger greenhouse operations such as Greenhouse 5 (Priva) and Greenhouse 6 (Argus) have a control system with a weather station. These control systems are programmed to effectively control the greenhouse environment with minimal energy usage. However, these control systems are usually prohibitively expensive for smaller greenhouse operations.

6.3.3 Heating

Energy spent on heating greenhouses in Nova Scotia ranged from 65 and 82% of the total energy consumption. The most common heating fuel used in Nova Scotia is furnace oil, and larger operations such as # 9 and # 6 used wood chips (with at least 30% moisture content). In the past decade, greenhouse operations like # 2 and # 3 have switched to wood pellet from fuel oil #3 as the primary fuel source.

Approximately 10 to 15% of the total energy is attributed to electrical energy for circulation fans, unit heaters, and circulation and fuel pumps. In a centralized heating system, over 70% of the greenhouses used unit heaters, with heat transported in the form of hot water or steam (# 7). Whereas, large vegetable operations such as #5 use pipe-heating systems, where these pipe also serve as a rails for carrying carts.

In 80% of the freestanding greenhouse operations there were individual oil fired boilers located in each greenhouse. In operations that have upgraded to a centralized heating system, these furnaces are typically used as a backup only. CO_2 enrichments are more common in vegetable and cut flower operations. CO_2 enrichments provided from propane combustion were used for heating purposes as well.

6.3.4 Others

The above-mentioned categories (lighting, heating and ventilation) are the major energy consuming components in greenhouse operations; other categories include the irrigation system (that involve large pumps to circulate nutrients and water), which only consumes between 0.5 to 1.5 % of the total energy. Soil mixers and vegetable wrappers account for less than 1 % of overall energy use. In some small floriculture operations, computers, printers and general office equipment account for about 2 to 6 % of the total energy consumption.

6.4 ENERGY MONITORING IN GREENHOUSE OPERATION 2 (CASE STUDY)

This operation specialized in growing and selling outdoor ornamental plants, nursery stock, and vegetables and herbs, utilizing seven separate greenhouses and a planting room. Due to the rising cost of furnace oil, a pellet furnace was installed in 2006 to reduce the energy overheads and for the business to become a more sustainable and environmentally friendly operation.

6.4.1 Heating System Monitoring with WELServer

A WELServer was installed in mid - December 2011, Figure 12, since the boiler starts operation before winter to keep water in the system above freezing. The biomass boiler serves Greenhouses 5 to 7 and the planting room directly, and was linked with a heat exchanger through a closed loop, servicing Greenhouses 1 to 4, with an oil furnace for back-up. The heat exchanger was installed as the pellet furnace operates with a pressurized loop and the oil furnace with an unpressurized loop.

The total operating time, from December to May was 1,600 hours with the oil furnace only required for 58 hours to supplement the pellet furnace (that operated 499 hours), mainly in December. Operating at a 30% fuel feed rate, the pellet boiler took approximately five hours to reach an operating temperature of 80 °C, and two and a half hours from a starting temperature of 26 °C with a difference of 2 to 5 °C in the supply and return temperatures.

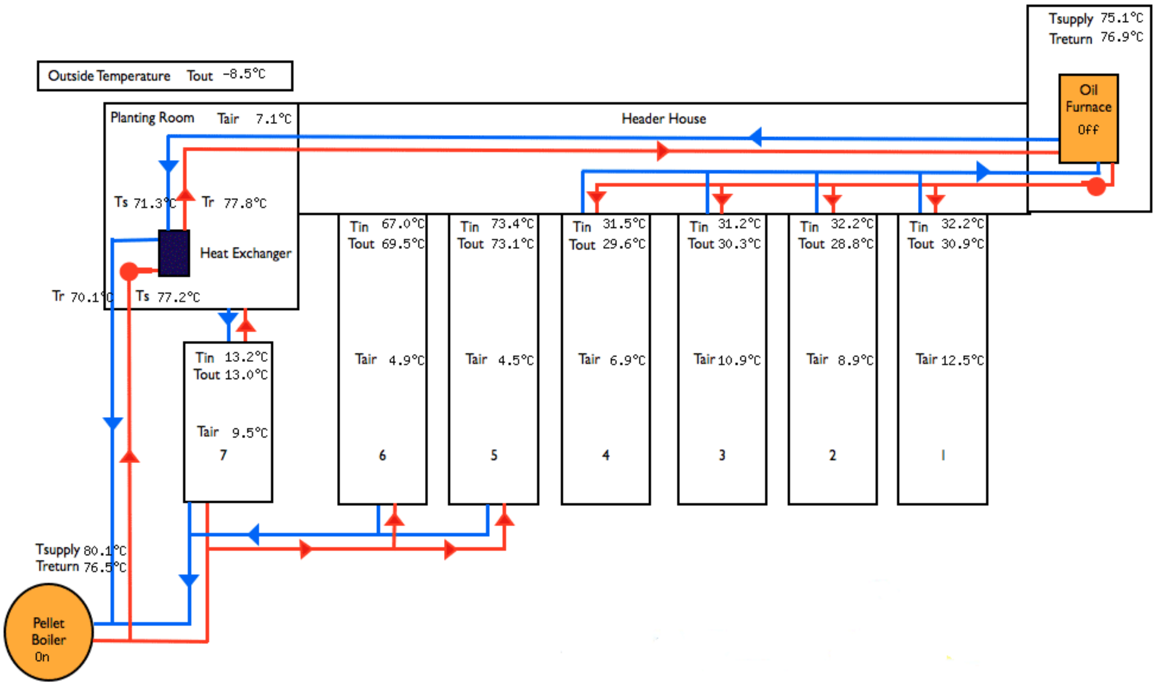


Figure 12. WELServer Schematic representation of Greenhouse Operation #2.

As the boiler was heating to reach operating temperature (steady state), the circulation pumps operated and slowly raised the greenhouses to the desired air temperatures. For example, one of the greenhouses reaches the desired temperature of 38 ^{o}C within three hours. The biomass boiler heated all the greenhouses, with oil heaters being used to adjust the greenhouses requiring different temperatures. Using automatic feed augers and a low feed rate helps to reduce operating costs and emissions. Having reached operating temperature, the boiler fluctuates around the temperature set point, as it tried to keep up with the heat demand in the production area.

6.4.2 Boiler Assessment with Grass Pellet Fuel

A Pelco Boiler is a CSA certified hot water biomass boiler, designed for domestic, agricultural, commercial and industrial applications. The Pleco boiler was primarily designed to burn coal, corn and wood pellets and is equipped with features such as flue cleaning, feed and ash augers and other protection systems controlled by a Programmable Logic Control (PLC). Heat demand of the load is supplied by continuously controlled ON-OFF cycles, at a fixed feed rate based on peak demand. A study was performed to technically assess the feasibility of using grass as a fuel for the Pelco Hot Water Biomass Boiler with no added features. For initial assessment, overwintered reed canary grass grown in the field of the greenhouse operator was used as the fuel. The crop was overwintered to reduce alkali metals and other fuel bound inorganic elements to reduce emissions and other boiler issues (such as clinkering, fire-tube deposition, corrosion, etc.). From the flue gas analysis based on the wood and grass pellet combustion showed that the grass pellets had three times more NOx emissions and ten times higher SO_2 emissions compared to wood pellets.

For testing solid fuel combustion appliances having a cyclic pattern as in Pelco Hot Water Boiler, exit gas temperatures and other flue gas contents were measured at a regular intervals of not more than 10 min. The average total flue gas loss were calculated and used in conjunction with other losses to determine the average efficiency.

For wood and grass fuel, the boiler flue gas composition was measured at regular intervals (1 minute) with a multicomponent flue gas analyzer, Eurotron's UniGas 3000+. The analyzer uses electrochemical sensors for the measurement of different gas concentrations.

The CO_2, CO, O_2, SO_2, NO, NOx concentrations along with the exhaust temperature were recorded every minute, from which excess air and combustion efficiency were calculated using indirect method. The average of flue gas parameters measured from the Pelco Hot Water Boiler, when both wood and grass was used as a fuel is presented in Table 2.

For comparison, the data obtained from both the wood and grass fuel were normalized. All of the results were calculated for standard conditions STP (273 K, 1013 kPa). The emission values were normalized to volumetric oxygen content of 13% in the exhaust gas is given in Table 3. The results indicate that NOx emission levels are 3 times higher in grass and SO_2 approximately 12 times higher than found in wood. Based on the combustion temperature, it may be concluded that NOx emissions are mainly due to fuel Nitrogen and sulfur content.

Table 2. Average of flue gas parameters measured from Pleco Boiler for wood and grass pellet fuel.

Fuel	O_2[1], %	CO_2[2], %	CO[3], ppm	Tg[4], °C	Eff.[5], %	Ta[6], °C	Td[7], °C	Los.[8], %	NO[9], ppm	NOx[10], ppm	SO_2[11], ppm
Wood	17.2	3.7	147	88.2	74.9	8.4	79.8	25.1	25	25	3
Grass	15.2	5.6	270	174.2	69.5	7.7	166.5	30.5	106	109	58

[1] Percentage oxygen in flue gas;
[2] Percentage carbon-dioxide in flue gas;
[3] Carbon monoxide in ppm;
[4] Flue gas temperature;
[5] Efficiency;
[6] Ambient temperature;
[7] Difference in temperature;
[8] Net loss
[9] Nitrous-oxide in ppm;
[10] Oxides of nitrogen in ppm;
[11] sulfur-dioxide in ppm

Table 3. Flue gas emissions normalized to 13% O_2 (ref.)

	CO	**NO**	**NOx**	**SO_2**
	ppm	ppm	ppm	ppm
Wood	309	53	53	6
Grass	372	146	150	80

6.5 EMISSIONS AND COMBUSTION PERFORMANCE OF AGRO-PELLETS AGAINST PREMIUM WOOD PELLETS

6.5.1 Fuel Pellet Properties

Four experimental agro-pellets and one premium quality wood pellet were characterized with ASTM standard test methods used for the analysis of wood fuel (ASTM E870-82 (2013)).

Table 4. Results of proximate analysis and ultimate analysis on wood, barley straw, reed canary grass, switch grass and wheat straw.

	Wood	**Barley**	**Reed**	**Switch**	**Wheat**
Proximate Analysis					
Moisture, % (ar)	9.04	10.87	10.21	10.91	11.39
Ash, % (db)	0.74	4.83	6.97	3.05	6.23
Volatile Matter,% (db)	78.34	75.72	74.09	79.22	75.01
Fixed Carbon, % (db)	20.92	19.44	18.93	17.73	18.77
Ultimate Analysis					
Carbon, % (db)	48.75	44.90	42.20	44.80	43.40
Hydrogen, % (db)	6.54	6.15	5.90	6.10	6.07
Nitrogen, % (db)	0.05	0.68	0.60	0.28	0.45
Sulfur, % (db)	0.24	0.0041	0.0072	0.0025	0.0036
Oxygen, % (db)	44.12	48.30	51.30	48.80	50.00
Calorific Value					
HHV (MJ/Kg) (db)	18 .42	18.31	17.31	18.24	17.81

ar: as received
db: dry basis (Oven dried at 105 °C for 24 hours)

6.5.2 Profile of Flue Gas Parameters

The graphs in Figures 13 and 14 show the profiles of various parameters such as O_2, NO, SO_2, T_{gas} and CO from the flue gas analyzer, obtained while burning wood and wheat pellets.

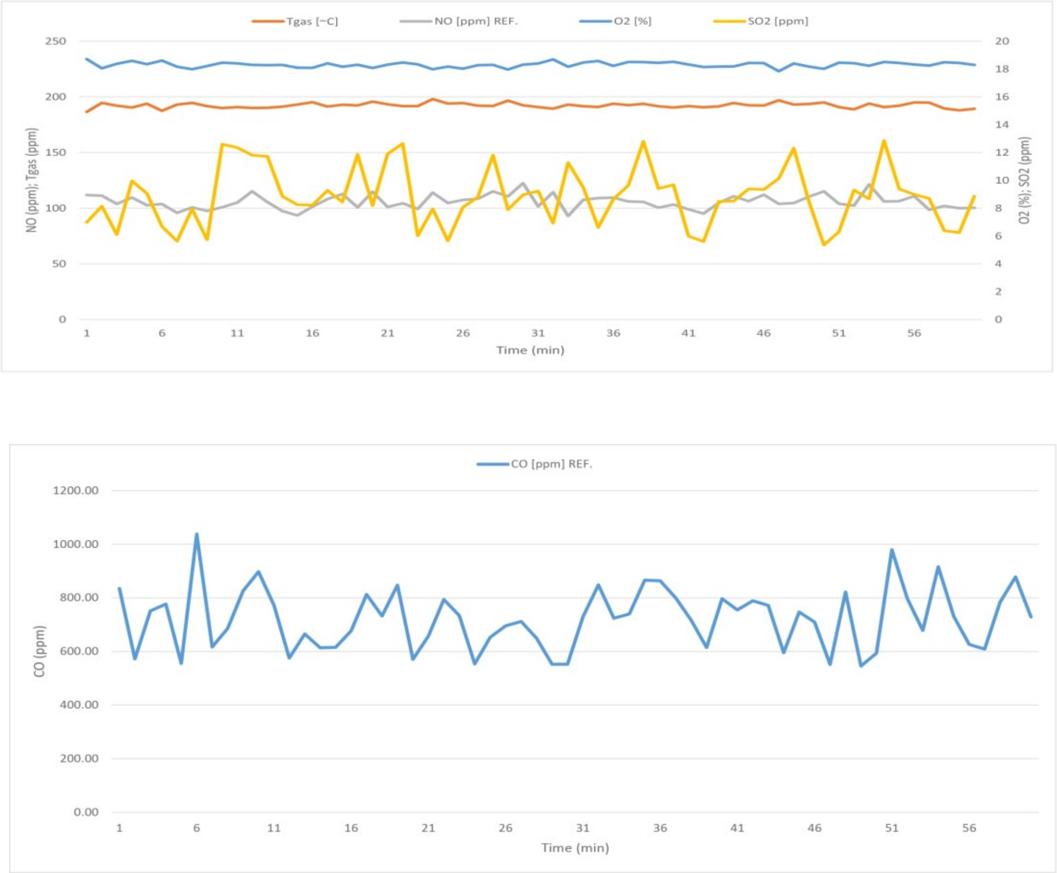


Figure 13. Graph showing the profile of flue gas parameters during the steady state combustion of wood.

Figure 14. Graph showing the profile of flue gas parameters during the steady state combustion of wheat straw.

On comparing the fuel burn profile of wheat straw and wood pellets it was observed that the NO and CO emission from the flue gas were significantly different. The NO emissions varied over 100 ppm in wood, whereas in wheat straw it varied between 100 and 350 ppm (range – 250 ppm). Likewise, CO which is a primary indicator of incomplete combustion, ranged over 400 ppm in wood and 10000 ppm in wheat straw.

This indicated that there is a higher incomplete combustion in wheat straw compared to wood. Hence, better combustion was observed in wood compared herbaceous biomass pellets.

Gaseous Emissions

Carbon monoxide, oxides of nitrogen and sulfur were normalized to 13% volumetric oxygen content in the exhaust gas and presented in Table 5.

i. Carbon-monoxide

Carbon-monoxide emissions of 2884.7 ppm were recorded during combustion of barley pellets. Wheat, switch grass and reed canary grass had a similar emissions around 1800 ppm followed by wood pellets with much lower average emissions of around 720 ppm.

Table 5. Results of gaseous and particulate emissions on wood, barley straw. Reed canary grass, switch grass and wheat straw.

	Wood	**Barley**	**Reed**	**Switch**	**Wheat**
CO [ppm] *	721.65	2884.75	1783.45	1707.07	1911.35
SOx [ppm] *	8.84	0	0	0	0
NOx [ppm] *	105.69	436.43	399.55	308.3	267.45
Tgas [°C]	192.25	224.62	184.14	221.48	166.95
Efficiency [%]	48.33	50.21	47.64	49.86	51.25

* normalized to reference oxygen of 13%

The carbon-monoxide profile for wood, was very consistent, however, fluctuated significantly with the agro pellets. Carbon-monoxide emissions are predominantly due to incomplete combustion that may be caused by factors such as poor combustion conditions (and/or) insufficient air supply.

ii. Oxides of Nitrogen

Barley (436.43 ppm) had the highest NOx emissions, followed by reed (399.55ppm), switch (308.30ppm), wheat (267.45ppm) and wood (105.69ppm). NOx emissions are predominantly due to the fuel bound nitrogen content, since the combustion temperature in this boiler was much lower than 1200^{o}C. Comparison of the NOx emission profiles under steady state conditions revealed that wood had short range variations, however a much larger range was experienced with the agro pellets.

iii. Oxides of Sulfur

Sulfur-dioxide emissions from the agro-pellets were lower than the detectable limit during steady state conditions, however, emissions of (8.84 ppm) were detected for wood. Comparing the ultimate analysis results with other similar studies, sulfur levels in the agro-pellets were significantly low. Though ultimate analysis was not performed on the wood pellets, it believed that the sulfur in wood should be significantly higher than other agro-pellets tested in this study.

6.5.3 Particulate Emissions

Reed canary grass had the highest particulates emissions of 483.75 mg/Nm^3 on average, significantly higher than switch grass and wheat straw with 334.76 mg/Nm^3 and

302.08 mg/Nm^3 respectively, with Barley straw exhibiting the lowest at 120.10 mg/Nm^3. The total suspended particulate was the lowest in wood, 68.02 mg/Nm^3 on an average. Comparison of wood pellets with other agro pellets, particulate emissions are typically two to eight times higher in agro pellet than wood pellets.

6.5.4 Combustion Performance

The efficiencies from the combustion of wood, wheat straw, barley straw, switch grass and reed canary grass were not significantly different from one another at 5% level of significance. However the efficiency in the pellet furnace was much lower that the other pellet boilers reported in literature.

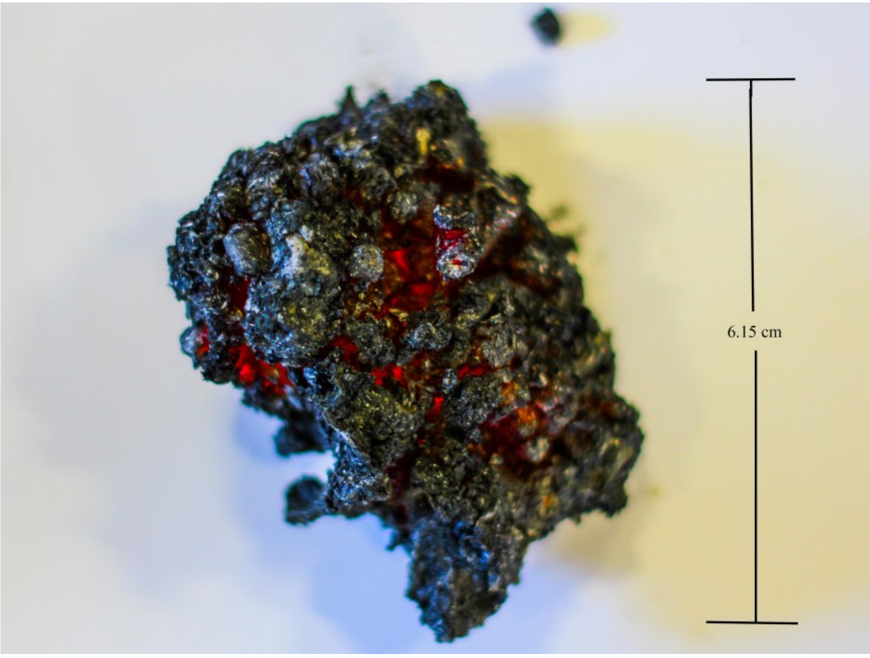


Figure 15. A fraction of solid mass collected from the burn pot during the combustion of agro-pellets (Reed Canary pellets).

Moreover, an unusual combustion behavior was observed during the combustion of agro-pellets, at combustion temperatures in excess of 600°C, pellets were sticking to one-another and formed a hard mass. As the agitator in the burn pot was turned on, these solid masses of pellets were collected together; the pellets failed to ash completely and drop down to the ash receiver.

The pellets accumulated and seized the agitator. Hence to continue operation, part of the mass had to be removed from the burn pot at regular intervals. A fraction of collected mass is shown in Figure 15, whereas with wood pellets this phenomenon was not observed.

6.6 CONTROLLED BATCH LEACHING CONDITIONS FOR OPTIMAL UPGRADING OF AGRICULTURAL BIOMASS

Ash, nitrogen, sulfurs, chlorine and other alkali metals such as potassium, sodium, magnesium and calcium are some of the potential elements that contribute to higher emissions (NO_x, SO_2, and particulate) and other boiler issues (slagging, clinkering and corrosion of boiler heating surfaces). Ultimate analysis and ash analysis on a per oxide basis were carried out on the four unmodified feedstock used for the experiment, the results of which are reported in Tables 6 and 7. These results provide a benchmark from which to determine the relative changes due to the leaching experiment.

Table 6. Ultimate analysis for the samples used, expressed as percentage of initial dry mass and chlorine expressed in parts per million (ppm).

	C %	**H %**	**O %**	**S %**	**N %**	**Cl, ppm**
Barley	46.50	6.15	45.79	0.24	1.32	2446.2
Switch Grass	46.00	6.1	46.41	0.28	1.21	888.1
Wheat	45.53	6.07	47.38	0.3	0.72	5528.5
Reed Canary	45.00	5.9	47.15	0.31	1.64	2295.5

Table 7. Ash analysis and alkali metal composition for the samples, expressed in milligram per gram of dry sample.

	Ash	**Mg**	**Ca**	**K**	**Na**
	mg/g	**mg/g**	**mg/g**	**mg/g**	**mg/g**
Barley	56.63	0.93	3.38	12.14	0.595
Switch Grass	30.5	1.22	2.6	2.03	0.248
Wheat	68.73	0.98	2.47	9.76	0.994
Reed Canary	73.17	1.07	2.47	8.5	0.081

The results reported in Tables 6 and 7 show that the overall ash content was lower in switchgrass than the other three feedstock and the potassium (K) and chlorine (Cl) were significantly higher in wheat, barley and reed canary grass than found in switch grass.

The results of the leached feedstock representing each of the experimental variables (time and temperature) were compared to the unleached control feedstock samples presented as % x-reduction, which can be defined by the following equation (7),

$$\%x\ reduction = \frac{(x_{leached} - x_{unleached})}{x_{unleached}} * 100 \quad \text{----- (7)}$$

Where, % reduction in ash and other elemental concentration was analyzed using central composite full factorial design.

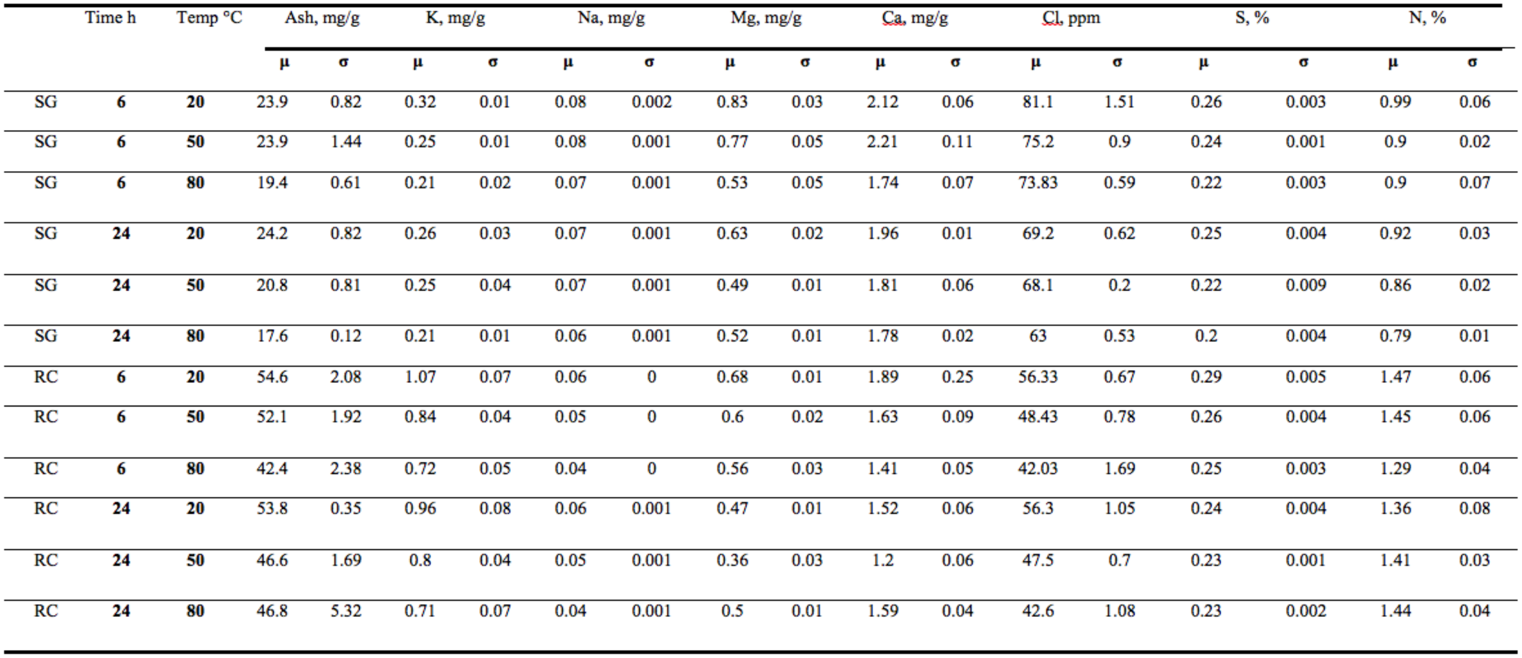
6.6.1 Energy Crop

Switch grass and reed canary grass are purpose-grown crops used for the production of bio renewable energy. Improving the quality of biomass produced by these energy crops is a key for these to be predominantly used in the energy sector. Leached switch grass and reed canary grass were tested for ash, nitrogen, sulfur and other alkali metals and the data is presented in Table 8.

i. Switch Grass

Potassium, chlorine, sodium and sulfur had a reduction of 90%, 93%, 75% and 27% respectively, when subjected to a water temperature of 80^{o}C for 24 hours. Whereas, in the case of magnesium and calcium the average reduction of 57% occurred at each of the following three conditions of 80^{o}C for 6hours, 50^{o}C for 24hours and 80^{o}C for 24hours residence time.

Table 8. Energy Crops (Switch Grass and Reed Canary Grass) – Mean (μ) and standard deviation (σ) for Ash, K, Na, Mg, Ca, S and N presented for different temperature and resident time combinations. SG – Switch Grass; RC – Reed Canary Grass.



	Time h	Temp °C	Ash, mg/g		K, mg/g		Na, mg/g		Mg, mg/g		Ca, mg/g		Cl, ppm		S, %		N, %	
			μ	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**
SG	**6**	**20**	23.9	0.82	0.32	0.01	0.08	0.002	0.83	0.03	2.12	0.06	81.1	1.51	0.26	0.003	0.99	0.06
SG	**6**	**50**	23.9	1.44	0.25	0.01	0.08	0.001	0.77	0.05	2.21	0.11	75.2	0.9	0.24	0.001	0.9	0.02
SG	**6**	**80**	19.4	0.61	0.21	0.02	0.07	0.001	0.53	0.05	1.74	0.07	73.83	0.59	0.22	0.003	0.9	0.07
SG	**24**	**20**	24.2	0.82	0.26	0.03	0.07	0.001	0.63	0.02	1.96	0.01	69.2	0.62	0.25	0.004	0.92	0.03
SG	**24**	**50**	20.8	0.81	0.25	0.04	0.07	0.001	0.49	0.01	1.81	0.06	68.1	0.2	0.22	0.009	0.86	0.02
SG	**24**	**80**	17.6	0.12	0.21	0.01	0.06	0.001	0.52	0.01	1.78	0.02	63	0.53	0.2	0.004	0.79	0.01
RC	**6**	**20**	54.6	2.08	1.07	0.07	0.06	0	0.68	0.01	1.89	0.25	56.33	0.67	0.29	0.005	1.47	0.06
RC	**6**	**50**	52.1	1.92	0.84	0.04	0.05	0	0.6	0.02	1.63	0.09	48.43	0.78	0.26	0.004	1.45	0.06
RC	**6**	**80**	42.4	2.38	0.72	0.05	0.04	0	0.56	0.03	1.41	0.05	42.03	1.69	0.25	0.003	1.29	0.04
RC	**24**	**20**	53.8	0.35	0.96	0.08	0.06	0.001	0.47	0.01	1.52	0.06	56.3	1.05	0.24	0.004	1.36	0.08
RC	**24**	**50**	46.6	1.69	0.8	0.04	0.05	0.001	0.36	0.03	1.2	0.06	47.5	0.7	0.23	0.001	1.41	0.03
RC	**24**	**80**	46.8	5.32	0.71	0.07	0.04	0.001	0.5	0.01	1.59	0.04	42.6	1.08	0.23	0.002	1.44	0.04

Nitrogen content in switch grass was reduced by an average 30% with no significant difference between 50°C and 80°C at both 6 and 24 hours resident time. Whereas, the overall ash content reduced by an average 49% at 80°C at both 6hours and 24 hours residence time.

ii. Reed Canary Grass

Reed canary grass had a maximum chlorine reduction of 97% and there was no significant difference between the time and temperature combination. Similarly, the interaction between the two factors was not significantly different for sodium and potassium, which indicates that there was a consistent decrease to a maximum of 92% and 48% respectively in potassium and sodium with increase in temperature and time. When magnesium, calcium, nitrogen and overall ash are considered, reduction was inconsistent. For example, nitrogen decreases with an increase in temperature at 6 hours, whereas nitrogen increased with increase in temperature at 24 hours residence time. However, in the case of sulfur there was a consistent percentage reduction up to a maximum of 28% with time and temperature.

6.6.2 Agricultural Residue

Abundantly available agricultural residue such as wheat and barley straw could substantially serve bioenergy market demands. The fuel properties of leached wheat and barley straw are reported in Table 9.

Table 9. Agricultural Residue (Barley and Wheat) – Mean (µ) and standard deviation (σ) for Ash, K, Na, Mg, Ca, S and N presented for different temperature and resident time combinations. B – Barley; W – Wheat;

	Time h	Temp °C	Ash, mg/g		K, mg/g		Na, mg/g		Mg, mg/g		Ca, mg/g		Cl, ppm		S, %		N, %	
			µ	**σ**	**µ**	**σ**	**µ**	**σ**	**µ**	**σ**	**µ**	**σ**	**µ**	**σ**	**µ**	**σ**	**µ**	**σ**
B	**6**	**20**	31.5	2.88	2.33	0.09	0.18	0.001	0.84	0.02	2.72	0.05	326.4	6.72	0.24	0.002	0.98	0.05
B	**6**	**50**	26.0	2.23	1.79	0.08	0.15	0	0.67	0.01	2.34	0.07	288.3	3.27	0.22	0.004	0.92	0.08
B	**6**	**80**	18.2	2.37	1.61	0.13	0.14	0.001	0.6	0.02	2.25	0.05	268.5	0.7	0.21	0.008	0.89	0.08
B	**24**	**20**	28.1	2.59	1.59	0.14	0.17	0.004	0.63	0.03	2.36	0.13	229.6	3.41	0.23	0.006	1.01	0.04
B	**24**	**50**	15.1	2.11	1.17	0.1	0.14	0.003	0.33	0.04	1.45	0.04	221.7	0.8	0.21	0.001	0.79	0.05
B	**24**	**80**	14.3	2.11	0.8	0.04	0.13	0.001	0.44	0.02	1.73	0.06	200.4	0.89	0.19	0.005	0.83	0.05
W	**6**	**20**	38.8	1.85	1.39	0.07	0.29	0.003	0.82	0.03	1.79	0.07	569.0	1.46	0.27	0.005	0.53	0.04
W	**6**	**50**	35.0	0.67	1.21	0.14	0.27	0.001	0.65	0.01	1.67	0.02	495.7	3.68	0.24	0.002	0.49	0.05
W	**6**	**80**	26.3	1.4	1.12	0.16	0.21	0.001	0.6	0.03	1.59	0.13	389.2	5.4	0.22	0.002	0.57	0.04
W	**24**	**20**	39.2	1.76	0.91	0.08	0.24	0.002	0.55	0.03	1.52	0.07	485.2	5.16	0.25	0.002	0.59	0.06
W	**24**	**50**	25.0	3.94	0.88	0.03	0.22	0.002	0.38	0.03	1.13	0.07	484.9	5.79	0.22	0.002	0.53	0.02
W	**24**	**80**	24.0	1.7	0.67	0.09	0.19	0.001	0.58	0.04	1.49	0.11	440.4	2.55	0.2	0.003	0.53	0.02

i. Barley

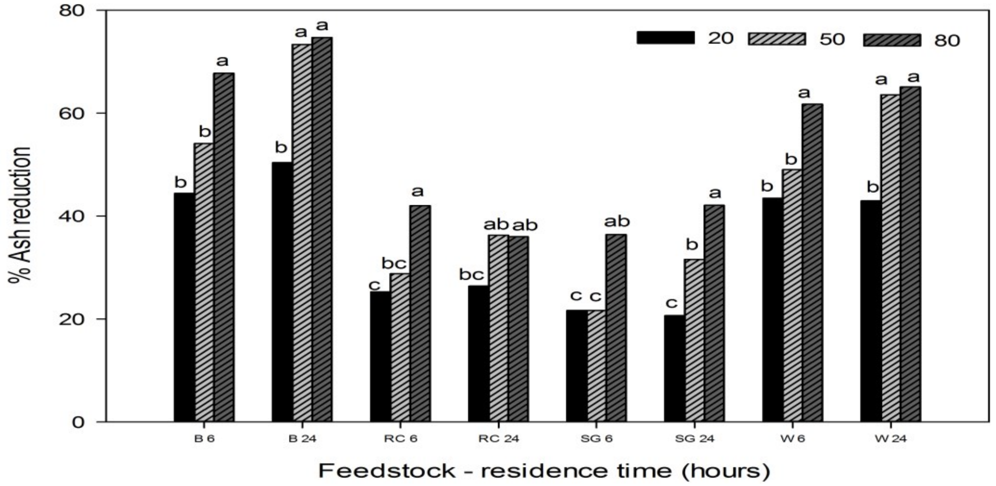
Barley had a maximum ash reduction of 75% at 80^{o}C for 24hour residence time. A consistent reduction of 93% and 92% was observed for potassium and chlorine at 80^{o}C and 24hours residence time. Whereas, magnesium and calcium had a maximum reduction of 65% and 57% at 50^{o}C with 24 hours residence time.

Sodium and sulfur had a maximum reduction of 77% and 17% at 80^{o}C with both 6 hours and 24 hours residence time. Furthermore, nitrogen reduced by an average 35% at 50^{o}C and 80^{o}C with both 6hours and 24 hours residence time.

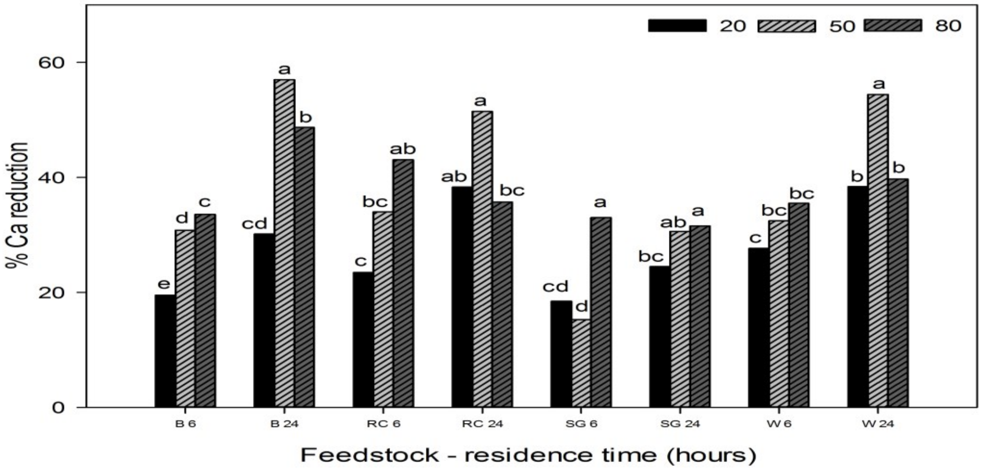
ii. Wheat

Similar to barley, the overall ash content reduced to an average of 63% with no significant difference between 80^{o}C at 24 hours, 50^{o}C at 24 hours and 80^{o}C at 6 hours. There was an inconsistent reduction in nitrogen with increase in time and temperature. Whereas, with magnesium and calcium a reduction of 40% was observed for a temperature of 50^{o}C and 24hours residence time. Unlike other feed stocks, chlorine reduced by up to 93% at 80^{o}C with 6 hours residence time. A reduction of 35% was observed when wheat was subjected to 80^{o}C and 24 hours residence time. The following column graph represent the responses such as ash, N, S, K, Na, Mg and Ca in which the factor combinations are significantly different.

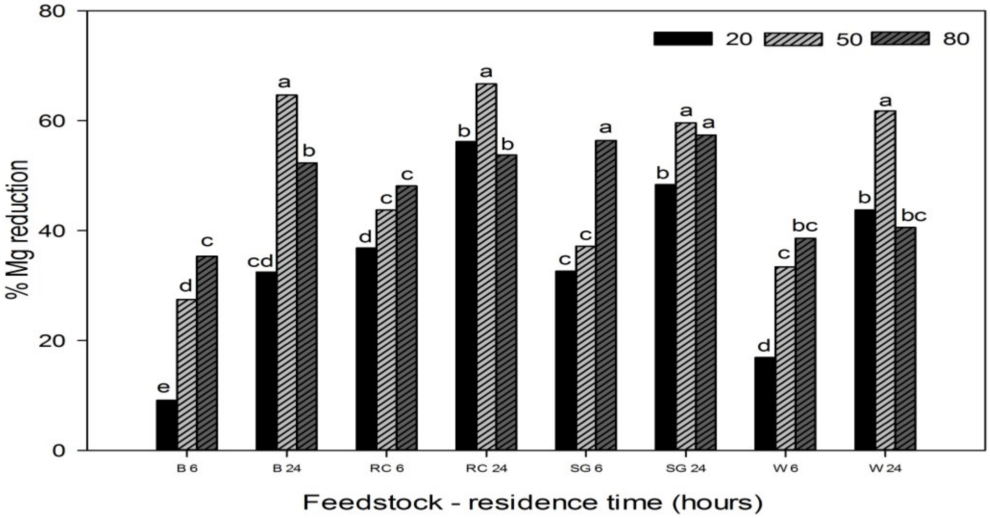
1.


% Ash reduction
0
20
40
60
80
20
50
80
B 6
B 24
RC 6
RC 24
SG 6
SG 24
W 6
W 24
Feedstock - residence time (hours)
b b a
b a a
c bc a
bc ab ab
c c ab
c b a
b b a
b a a

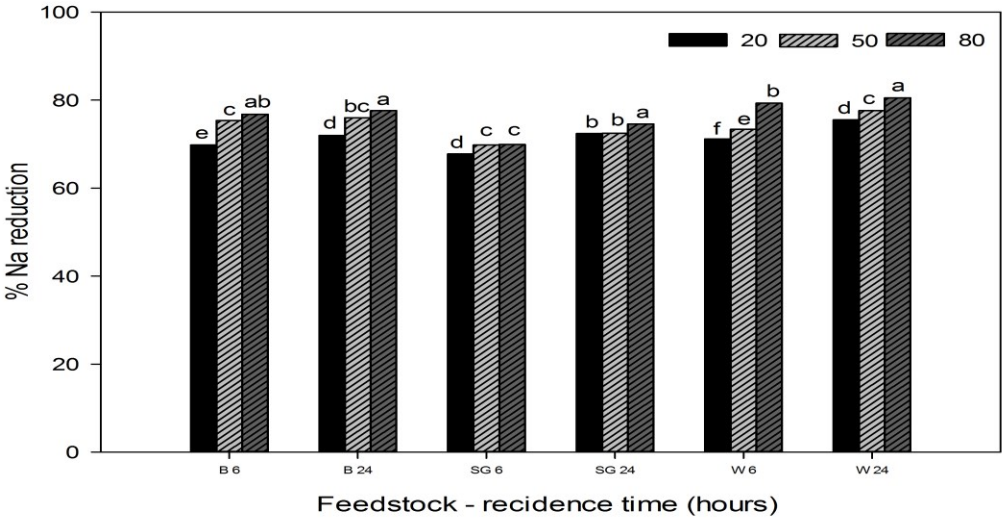
2.


% Ca reduction
0
20
40
60
20
50
80
B 6
B 24
RC 6
RC 24
SG 6
SG 24
W 6
W 24
Feedstock - residence time (hours)
e d c
cd a b
c bc ab
ab a bc
cd d a
bc ab a
c bc bc
b a b

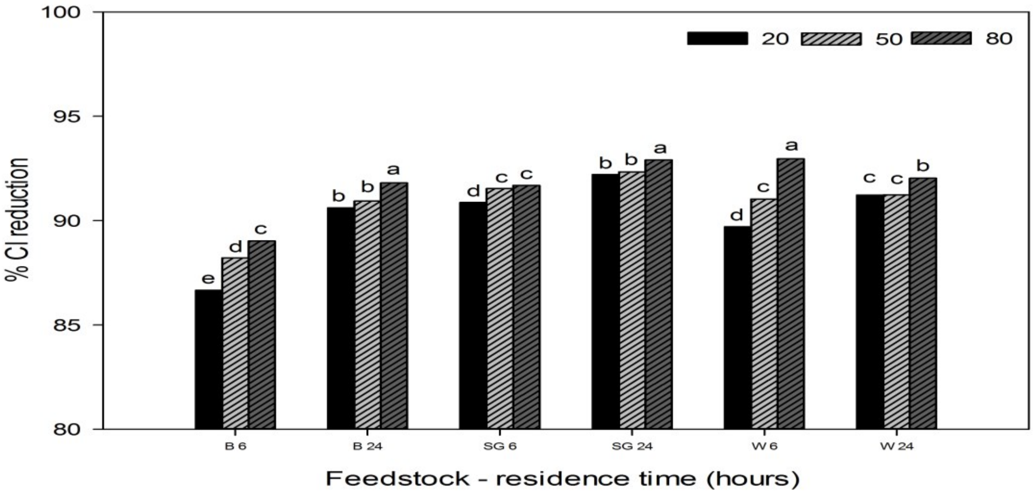
3.


80
60
40
20
0
% Mg reduction
20
50
80
e
d
c
cd
a
b
d
c
c
b
a
b
c
c
a
b
a
a
d
c
bc
b
a
bc
B 6
B 24
RC 6
RC 24
SG 6
SG 24
W 6
W 24
Feedstock - residence time (hours)

4.

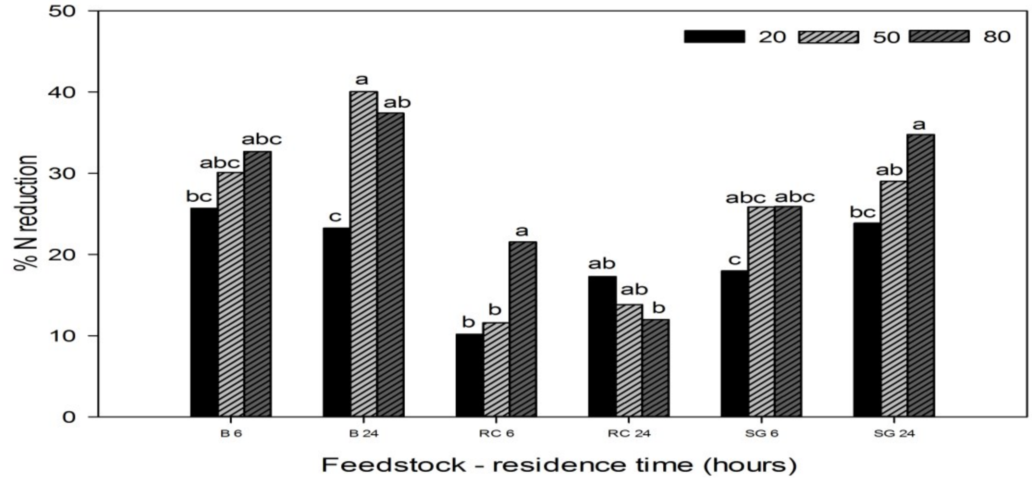

100
80
60
40
20
0
% Na reduction
20
50
80
e
c
ab
d
bc
a
d
c
c
b
b
a
f
e
b
d
c
a
B 6
B 24
SG 6
SG 24
W 6
W 24
Feedstock - recidence time (hours)

5



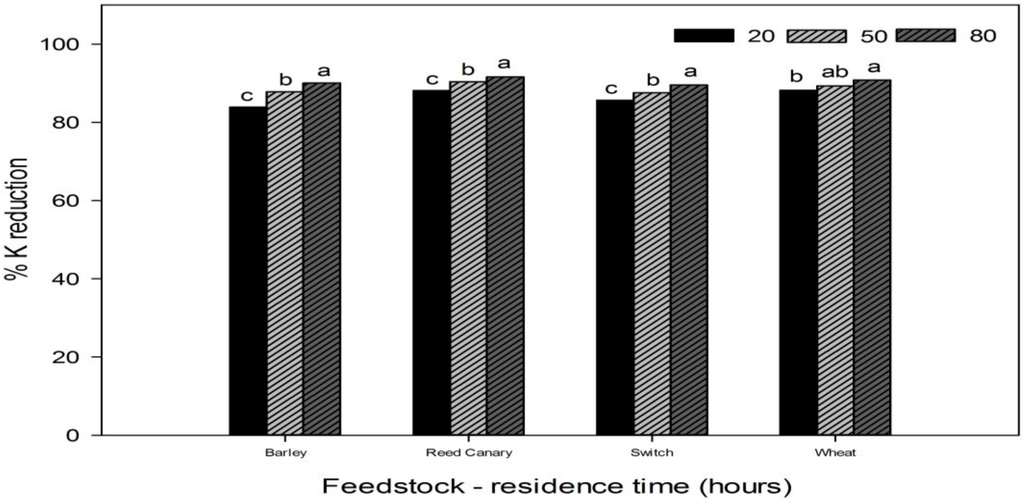
100
95
90
85
80
% Cl reduction
20
50
80
e d c
b b a
d c c
b b a
d c a
c c b
B 6
B 24
SG 6
SG 24
W 6
W 24
Feedstock - residence time (hours)

6



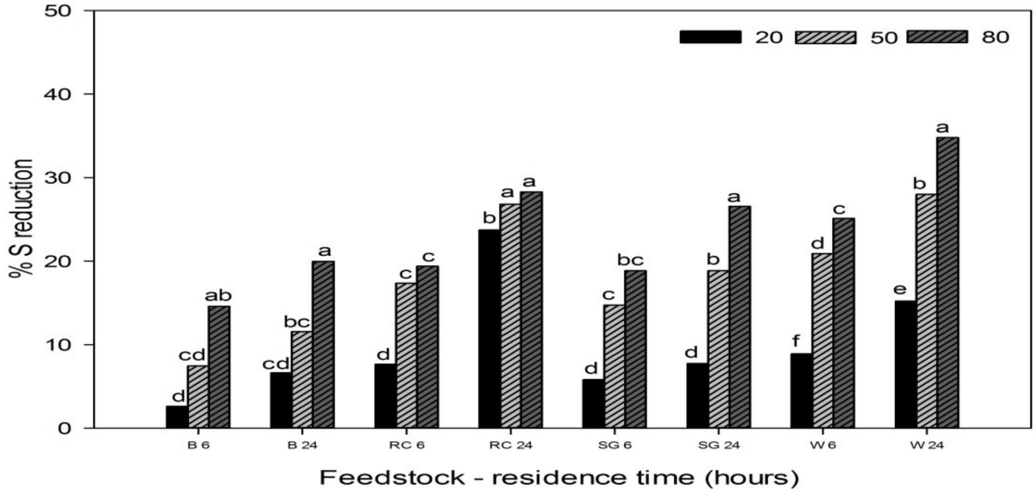
50
40
30
20
10
0
% N reduction
20
50
80
bc abc abc
c a ab
b b a
ab ab b
c abc abc
bc ab a
B 6
B 24
RC 6
RC 24
SG 6
SG 24
Feedstock - residence time (hours)

7



20
50
80
% K reduction
0
20
40
60
80
100
c
b
a
c
b
a
c
b
a
b
ab
a
Barley
Reed Canary
Switch
Wheat
Feedstock - residence time (hours)

8



20
50
80
% S reduction
0
10
20
30
40
50
d
cd
ab
cd
bc
a
d
c
c
b
a
a
d
c
bc
d
b
a
f
d
c
e
b
a
B 6
B 24
RC 6
RC 24
SG 6
SG 24
W 6
W 24
Feedstock - residence time (hours)

Figure 16. % reduction in Ash and other inorganic elements with respect to Resident time and Temperature factor. Treatments within a feedstock with same letters are not significantly different. Each column represents % reduction for each resident time and temperature factor combination.

6.7 COMPARISON OF GASEOUS AND PARTICLE EMISSIONS FROM LEACHED AND UN-LEACHED BIOMASS BRIQUETTES IN A DOMESTIC WOOD STOVE

6.7.1 Fuel Briquettes Properties

Heating value, proximate, ultimate and elemental analyses of the leached and un-leached briquettes were analyzed according to ASTM standards (ASTM E870-82 (2013)). Table 10 presents the results from proximate analysis, along with the heating value and bulk density of the briquettes used in this experiment. The moisture content (M) of the sample is measured as percent weight and calculated on an as received basis. Volatile matter (VM), Ash content (A) and Fixed Carbon (FC) of the sample are measured in percent weight and calculate on an oven dry basis. The ash content of the briquette samples ranged from 2.8 in leached switch grass to 7.3 in wheat.

However, there was no significant difference in HHV between the briquette samples in terms of Higher Heating Value (represented in MJ/Kg). The bulk density (BD) is one important physical properties of densified biomass briquettes and is highly comparable with the biomass pellets that typically range from 600 to 700 kg/m^3.

The ultimate and elemental analysis results are presented in Table 11, which have been calculated and presented on a dry basis. Potassium (K) and Chlorine (Cl) in the biomass samples are represented in ppm.

Table 10. Proximate analysis results with higher heating value and bulk density of leached and un-leached briquettes.

	M, (%, ar)	VM,(%,db)	A,(%, db)	FC,(%,db)	HHV,(MJ/Kg)	BD,(Kg/m^3)
Barley	9.55	73.48	5.46	21.07	18.54	663.72
Reed	13.09	70.68	7.29	22.03	18.03	745.28
Switch	12.39	76.37	3.39	20.24	18.59	573.40
Wheat	11.35	71.75	7.33	20.91	17.89	715.95
Leached Barley	9.11	77.01	4.49	18.5	18.23	562.44
Leached Reed	10.39	74.93	4.7	20.38	17.98	597.71
Leached Switch	9.66	78.1	2.88	19.01	18.94	689.31
Leached Wheat	11.21	74.63	5.31	20.06	17.64	565.57

ar:as received
db: dry basis

Table 11. Ultimate and Elemental Analysis results of leached and un-leached briquettes

	C (%)	**H (%)**	**N (%)**	**S (%)**	**O (%)**	**K (ppm)**	**Cl (ppm)**
Barley	44.9	6.15	0.68	0.0041	48.3	11.4	2411.8
Reed	42.2	5.9	0.6	0.0072	51.3	9.5	2238.1
Switch	42.2	6.1	0.28	0.0025	48.8	2.2	882.5
Wheat	42.2	6.07	0.45	0.0038	50	11.6	5559.4
Leached Barley	45.1	6.17	0.33	0.0038	48.4	1.7	732.8
Leached Reed	42.2	6.01	0.4	0.0053	50.2	1.3	199.6
Leached Switch	42.2	6.02	0.23	0.0024	49.7	0.4	93.4
Leached Wheat	42.2	6.18	0.43	0.0036	48.4	1.8	716

Literature indicates that NOx and SO_2 are predominantly due to the presence of fuel bound nitrogen and sulfur. From the ultimate analysis results it can be seen that both nitrogen and sulfur present in feedstocks were successfully leached out by washing with water. Likewise, potassium and chlorine in the samples were reduced significantly by washing in water. These results correspond with a number of experiments conducted in the past two decades [7, 9].

6.8 FLUE GAS PARAMETERS PROFILE

Gaseous emissions collected from the flue gas analyzer installed in the exhaust of the stove using Leached barley briquettes are shown in Figure 17. Both gaseous emission and particulate emissions should be performed during steady state condition. According to British Standard (BS 845-1:1987), a solid fuel fired boiler shall be considered that operating in steady state conditions only when there is a continuous flow of fuel and ash in and out of a boiler (or) if the drift in temperature does not exceed ± 10 ^{o}C/h. However, in a manual wood furnace the fuel is fed in batches and since the burn time is less than one hour, the steady state condition cannot be achieved as per the recommended procedure.

The burn profile shown in Figure 17 was consistent with all the fuel briquettes that were tested. The flue gas temperature reached its maximum in about 3 to 5 minutes and the temperature remained consistent within a range of ± 15 ^{o}C for approximately 35 to 40 minutes. The gaseous and particulate emissions were measured during this phase. It can be seen from Figure 17 that the NO_x emissions had a strong relation with stack temperature, whereas, SO_2 emissions spiked irregularly during the burn, making the SO_2 results inconsistent.

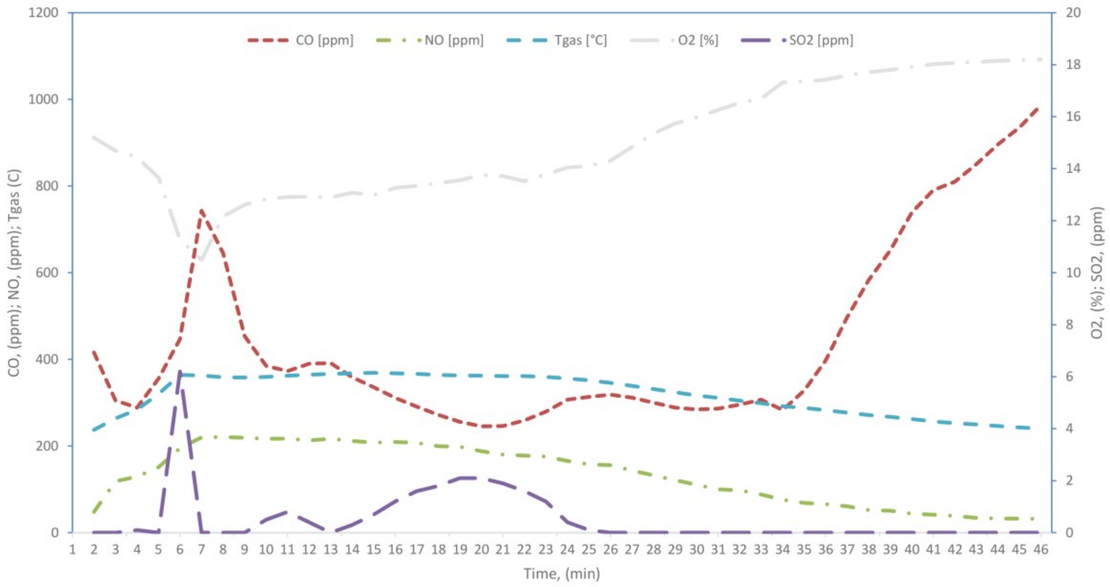


Figure 17. Graph that shows the profile of flue gas parameters during the combustion of leached barley briquettes.

6.9 GASEOUS EMISSIONS

i. CO (Carbon-monoxide)

Carbon-monoxide (CO) is an indicator of incomplete combustion. In a solid fuel combustion system, incomplete combustion may be a result of (a) poor furnace design,that leads to a low temperature in combustion chamber; (b) insufficient oxygen flow, in a forced draught furnace the combustion fan and induced draught fan may not be of proper size (or) in a natural draught furnace, faulty chimney setup (or) the chimney is not warm enough for a positive draught;(c). Poor mixing of oxygen and fuel, which is a common issue with solid fuel (in a liquid or a gaseous fuel the air and fuel can be mixed quite well with diffusers);(d) Moisture content of the fuel, higher moisture content could significantly affect combustion.

The CO emissions form the combustion of the leached and unleached briquettes were significantly different, whereas it was not significantly different between different feed stocks at the chosen level of significance ($\alpha = 0.05$). From the results it can be seen that CO from the leached briquette is about 50% less than that of the unleached briquettes and that none of the above mentioned factors seemed to have induced incomplete combustion. The reason for this reduction in CO in leached briquettes remains unknown.

ii. NOx (Oxides of Nitrogen)

The literature suggests that NOx (Oxides of Nitrogen) depend on two factors; (a) Fuel bound nitrogen content; and (b) Thermal NOx – produced when the combustion temperature is above 1200°C. Since, the briquettes were combusted in a domestic wood stove there is less probability of the combustion temperature exceeding 1200°C. Therefore, NOx emissions should be proportional to the fuel bound nitrogen content. However, from the graph shown in Figure 2, it can be seen that the relationship is linear.

Moreover, there was a strong association between NOx and the flue gas temperature (related to combustion temperature). However, the profile was different for each feedstock but they were consistent among the replicated results. Figure 20 presents a scatter plot that shows the relations between NOx emissions and fuel bound nitrogen content.

iii. SO_2 (Sulfur-dioxide)

SO_2 depends on the presence of fuel bound sulfur. Sulfur is considerably low compared to coal [6]. Hence, SO_2 emissions are much lower than the detectable range of 1 ppm most of the time during combustion. At high temperatures the SO_2 spiked irregularly. Though being inaccurate, the results of SO_2 have been averaged over the steady state period and are presented in Table 12.

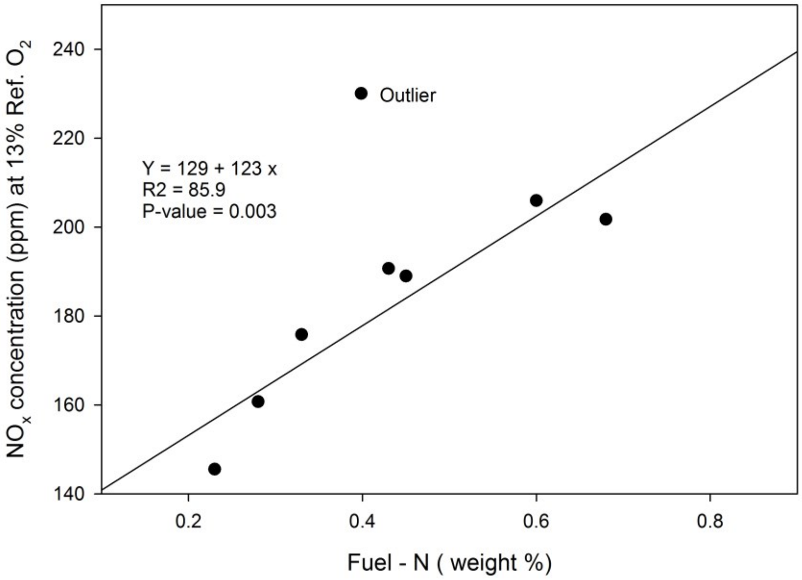


Figure 18. Scatter plot between NOx emission in ppm and fuel bound nitrogen content.

6.10 PARTICLE EMISSIONS

The particle emissions were highest for wheat, which was 76.78 mg/Nm^3 that had significant amount of potassium and chlorine. Over 80% of the potassium and chlorine leached out of the feedstock. This decrease in inorganics significantly reduced the particulate matter. There was a significant difference between Total Suspended Particulates (TSP) from the unleached and leached feedstock at alpha = 0.05 (level of significance). Similar to carbon-monoxide the TSP reduced to about 50% from unleached to leached feedstocks.

Table 12. Gaseous emission and other flue gas parameters are presented along with Total Suspended Particulates for the biomass briquettes under study.

	CO* (ppm)	**NO* (ppm)**	**SO_2* (ppm)**	**NO_x* (ppm)**	**O_2 (%)**	**T_{gas} (C)**	**Eff. (%)**	**TSP (mg/Nm^3)**
Barley	1534.2	195.73	0.15	201.77	14.75	315.51	60.8	72.78
Reed	1404.5	199.80	0.79	205.98	16.53	276.20	52.0	62.21
Switch	1369.8	155.88	2.20	160.71	15.59	312.44	52.7	61.46
Wheat	2027.2	183.35	0.36	189.02	15.75	287.24	58.9	76.68
Leached Barley	755.56	170.54	0.32	175.82	14.86	325.52	57.3	33.98
Leached Reed	594.60	221.03	3.41	227.85	16.03	283.64	56.0	33.63
Leached Switch	906.33	141.19	0.60	145.56	14.59	319.83	59.2	37.40
Leached Wheat	753.45	185.00	1.36	190.71	14.77	331.91	57.6	39.77

* normalized to reference oxygen of 13%

6.11 CONTRASTS

Contrasts were used to compare the means of fuel properties, particulate and gaseous emissions of leached and un-leached briquettes. Table 13 shows the statistical contrast comparing fuel properties of leached and un-leached biomass group along with percentage increase/decrease in ash, nitrogen and other fuel properties of leached biomass from un-leached biomass.

Table 13. Contrasts and percentage change comparing the fuel properties of leached and un-leached biomass.

Contrasts	P-Value	+ Increase / -Decrease
Ash (A)	<0.0001*	-25.95
Nitrogen (N)	0.0739**	-30.85
Sulfur (S)	0.5340	Not significant
Potassium (K)	<0.0001*	-85.01
Chlorine (Cl)	<0.0001*	-84.30

* indicates significant difference between contrasts

** indicates marginal significant difference between contrasts

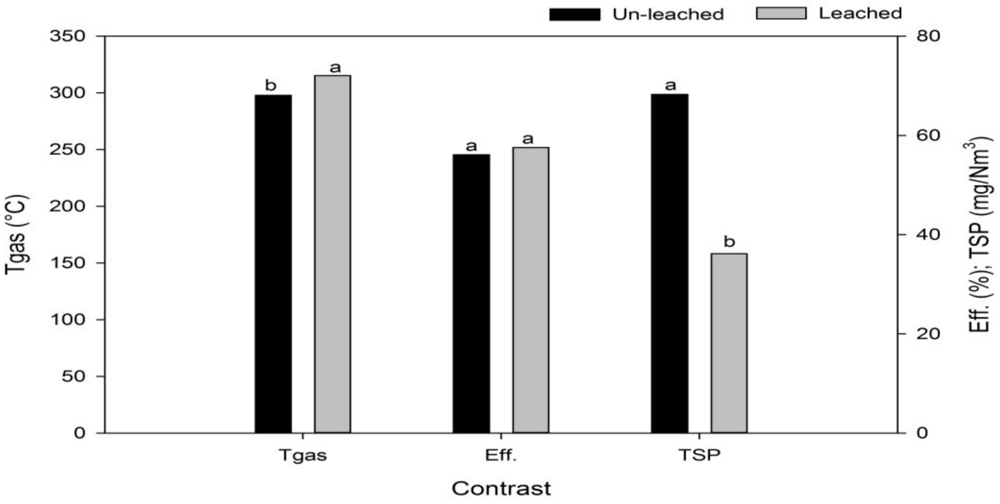
On comparing the leached and un-leached biomass as a group, significant difference was found with potassium (-85.01%), chlorine (-84.30%) and ash (-25.95%) and marginal significance with nitrogen (-30.85%). However, there was no significant difference between sulfur.

Table 14. Contrasts and percentage change comparing the flue gas parameters and particulate emissions for leached and un-leached briquettes.

Contrasts	P-Value	+ Increase / -Decrease
Carbon-monoxide (CO)	0.0438*	-52.49
Oxides of Nitrogen (NOx)	0.0097*	-2.31
Oxides of Sulfur (SOx)	<0.0001*	+62.83
Flue gas Temp. (Tgas)	0.0258*	+5.83
Efficiency (Eff.)	0.9138	(not significant)
Total Suspended Particulates (TSP)	<0.0001*	-46.99

* indicates significant difference between contrasts

1.



2.

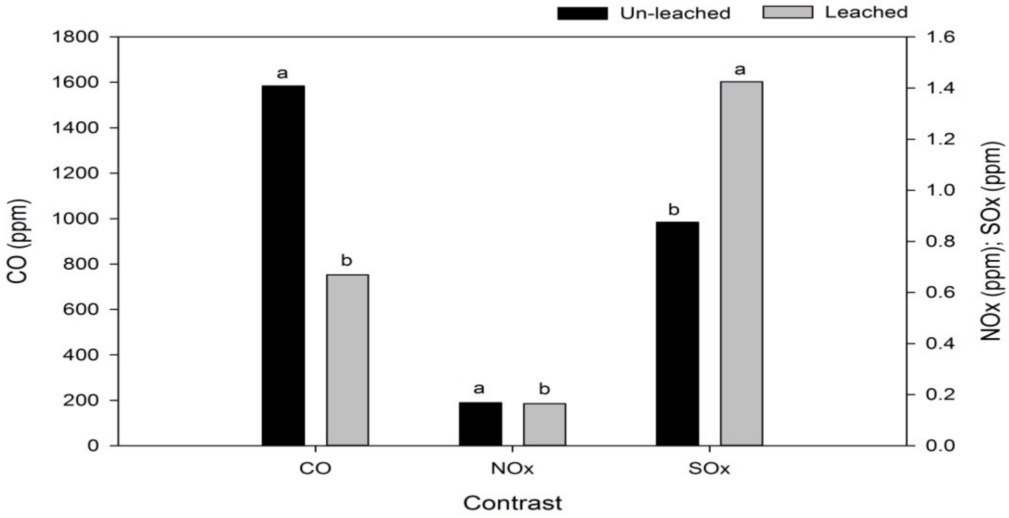


Figure 19. Graph representing the differences in flue gas parameters and total suspended particulates between leached and un-leached briquettes. (in a pair of columns, columns with same letters are not significantly different and columns with different letters are significantly different.)

Contrasts comparing gaseous and particulate emissions form leached and un-leached briquettes are presented in Table 14. Significant differences were found between CO, NOx, SOx, TSP and flue gas temperature. Whereas, the efficiency between the two groups were found to be insignificant. Further the differences between the groups are also shown in the Figure 19. Statistically significant group in the graph are represented with different letter. Whereas, statistically insignificant groups are represented with same letter.

Comparing fuel properties with reduction in gaseous and particulate emissions, percentage reduction in dependent emissions (NOx, SOx and TSP) were not as much as the independent fuel properties (fuel bound N and S, K and Cl) reduction.

6.12 COMBUSTION PERFORMANCE

i. Efficiency

In terms of combustion efficiency there were no significant difference between the leached and un-leached feedstocks. Un-leached barley and wheat and leached wheat, barley, reed and switch grass had efficiency around 60% and there were no significant different between them. Un-leached switch and reed combusted at an average efficiency of 52%.

ii. Other issues with combustion

There were no clinker or depositions found after all the test upon detailed investigation. However, as mentioned earlier it was hard to start with biomass briquettes alone in the combustion chamber. Before introducing briquettes, the combustion chamber has to be brought to temperature with a wood log burnt in to ambers.

Further, combustion of biomass briquettes generated a significant amount of ash compared to wood. The combustion chamber has to be cleaned after completing three combustion tests with biomass briquettes and start over again with wood log for heating up the combustion chamber.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The overall objective of this research project was to identify energy use in the greenhouse industry and suggest appropriate energy management opportunities that which will facilitate energy cost reduction in the Nova Scotia greenhouse industry. Greenhouse audits were conducted in ten greenhouses. Audit report containing energy management opportunities, approximate cost and savings were sent to the audited greenhouse operations. Reports present a number of energy saving opportunities on Lighting, Heating and Ventilation (Cooling) to save electricity. However, a major energy saving opportunity was “Switching to Alternate Fuel” commonly applicable for all the greenhouse operations studied for the research project primarily due to the following reasons,

- Heating cost is the largest energy cost in a typical greenhouse operation in Nova Scotia.
- Limited fuel options for the greenhouse operators in Nova Scotia.
- GHG emissions associated with fossil fuels typically used for heating Greenhouse operations
- Increasing price of imported light fuel oil.

There are few greenhouses operations that have switched from fuel oil #2 and #3 to wood pellets. In recent years, there has been a consistent increase in the price of wood pellets with fuel oil due to increasing demand for wood pellets in industrial and residential heating application. Furthermore, expansion of the raw material supply base for the wood pellet industry is not possible without environmental impacts because the raw materials are either directly or indirectly from forest resources. This creates an opportunity for herbaceous biomass (perennial grasses and agricultural residues) to be used as an alternate heating fuel resource for the greenhouse industry in Nova Scotia.

To evaluate the use of herbaceous biomass over wood pellets, an experiment was conducted comparing premium wood pellets against four agro pellets produced from four feed stocks native to Nova Scotia, which include wheat straw, barley straw, reed canary grass and switch grass, the following conclusions are made from the experiment,

- The carbon monoxide emissions were much higher for agro pellets compared to wood pellets.
- The NOx emissions were low in wood pellets compared to agro-pellets. Similarly, the profile for wood varied over a small range compared to agro-pellets. The NOx emissions appear to be highly correlated with fuel bound nitrogen content.
- Sulfur-dioxide emissions from agro pellets were less than the detectable limits and wood had a significantly high sulfur-dioxides emissions.
- Particulates derived from agro-pellets were two to eight times higher compared to wood.

- Unusual combustion behavior was observed during the combustion of agro-pellets. The pellets formed solid masses inside the burn-pot. This phenomenon was not observed in wood pellets.

Overall, wood pellets performed better in terms of emission and combustion. Hence, this suggests that grass and other agricultural biomass can potentially be used as a heating fuel only if the fuel property is modified.

To improve the fuel properties of herbaceous biomass, literature suggests various preprocess techniques such as overwintering, leaching, co-firing, torrefaction and pyrolysis. Batch leaching process was chosen to be appropriate for Nova Scotia based on economic and environmental conditions. An experimental study was conducted to investigate the impact of variables such as water temperature and residence time on the modification of reed canary grass, barley straw, switch grass and wheat straw with the objective of identifying the optimal conditions for creating an upgraded agricultural biomass feedstock suitable for combustion.

This experiment led to the conclusion that the most efficient method for batch leaching of inorganic material, particularly K and Cl, in the samples collected, switch grass and wheat straw is obtained at a temperature of 50°C with a 24 hour residence time. This temperature and time is the most effective, however more moderate conditions may be used depending on the ash content of the un-leached material. Previous literature has identified the leaching potential for reduction of these properties, but has not yet determined the effective conditions for performing this leaching. Using the method established in this experiment, switch grass and wheat straw can be prepared for combustion with the assurance that inorganic material content has been reduced sufficiently to safeguard against ash production, corrosion, slagging and harmful emissions.

Though previous experiment proves that leaching herbaceous biomass significantly reduces the inorganic materials and improves fuel property. An experiment was further conducted predominantly to investigate the impact of combustion characteristics of leached materials (against unleached material) and expand on the potential benefits of this process if in fact it results in a reduction in gaseous and particulate emissions during direct combustion. The following conclusions were drawn for the experiment comparing emissions and combustion performance of leached and unleached herbaceous biomass feedstocks in a Drolet XV Stove,

- Herbaceous Biomass briquettes cannot be combusted alone in a natural drought stove. The combustion system has to be brought up to temperature by some means (or) the biomass briquettes have to be co-combusted with wood or other briquettes that could initially start without smoldering.
- Carbon-monoxide from leached feedstock briquettes (752 ppm) is approximately 50 % of that from unleached briquettes (1584 ppm).
- Though NOx emissions were proportional to the fuel bound nitrogen content, the relationship was not completely linear. Moreover, there was a strong relationship

between NOx and flue gas temperature. The relationship was different for different feedstocks.

- The SO_2 was not proportional to the fuel sulfur content and was consistently less than the detectable limit (1 ppm) of the flue gas analyzer. It did spiked occasionally and this spike was averaged over the stady state period.
- Particulate matter had a strong relationship with potassium and chlorine content of the fuel. The fuel property of the feedstocks significantly improved during leaching. Hence, there was a significant difference between the TSP from leached and unleached feedstocks.

The results from the experiment suggest leaching to be an effective method to improve the fuel property, thereby improving the combustion performance and reducing gaseous and particle emission. This creates a opportunity to use agricultural residues and if need to expand the supply base, energy crops can be grown and used as a local fuel for residential and on-farm heating applications.

7.2 RECOMMENDATIONS FOR FUTURE WORK

The following are the point that should be considered,

1. This research focuses primarily on biomass (switching to biomass) to be a major energy management opportunity (EMO) for greenhouse industry to reduce the energy costs. There are many other operation specific EMOs that has to be

considered. Since, these EMOs are operation specific it is highly recommended to have the operation audited by a certified auditor for appropriate EMOs.

2. This research does not consider other fuel resources such as natural gas, as they are not available for the majority of greenhouse operations in Nova Scotia. It could be a potential option to be considered for reducing energy cost if available in future.
3. Emissions for biomass are predominantly due to inorganic elements that are dependent on soil and other environmental condition. These factors shall be considered for future studies.
4. Switch and reed canary grass are the energy crops of interest; Barley straw and wheat straw commonly available agricultural residue that were chosen for the study. In the future, energy crops such as Miscanthus and Napier grass and short rotation coppices such as willow and poplar could be available for consideration.
5. Using the production techniques described in this research, the briquettes were produced using less energy compared to pellets. However, the production of pellets might be economical at commercial and industrial scale.

REFERENCES

[1] "Greenhouse, Sod and Nursery," Statistics Canada, Tech. Rep. 22-202-X, 2013.

[2] "Toward a Greener Future: Nova Scotia's Climate Change Action Plan," Nova Scotia Department of Environment, 2009.

[3] W. J. Roberts, J. W. Bartok, E. E. Fabian and Simpkins.J. *Energy Conservation for Commercial Greenhouses* 1985.

[4] "State of the Forest report 1995-2005: Nova Scotia Forest in Transition" Nova Scotia Department of Natural Resources, Tech. Rep. FOR 2008-3, 2008.

[5] J. Burvall. Influence of Harvest Time and Soil Type on Fuel Quality in Reed Canary Grass (*phalaris arundinacea L.*). *Biomass Bioenergy 12(3),* pp. 149-154. 1997.

[6] B. M. Jenkins, R. R. Bakker and J. B. Wei. On the Properties of Washed Straw. *Biomass Bioenergy 10(4),* pp. 177-200. 1996. Available: http://dx.doi.org/10.1016/0961-9534(95)00058-5.

[7] B. Tonn, V. Dengler, U. Thumm, H. -. Piepho and W. Claupein. Influence of Leaching on the Chemical Composition of Grassland Biomass for Combustion. *Grass & Forage Science 66(4),* pp. 464-473. 2011. Available: http://ezproxy.library.dal.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=eih&AN=67002802&site=ehost-live.

[8] P. Ravichandran, D. Gibbs and K. Corscadden, "Controlled Batch Leaching Conditions for Optimal Upgrading of Agricultural Biomass,"*Journal of Sustainable Bioenergy Systems,* vol. 3, pp. 186-193, 2013.

[9] L. Deng, T. Zhang and D. Che. Effect of Water Washing on Fuel Properties, Pyrolysis and Combustion Characteristics, and Ash Fusibility of Biomass. *Fuel Process Technol 106(0),* pp. 712-720. 2013.

[10] Critten, D.L,Bailey, B.J,. A Review of Greenhouse Engineering Developments During the 1990s. *Agricultural and Forest Meteorology Agricultural and Forest Meteorology 112(1),* pp. 1-22. 2002.

[11] B. von Elsner, D. Briassoulis, D. Waaijenberg, A. Mistriotis, C. von Zabeltitz, J. Gratraud, G. Russo and R. Suay-Cortes . Review of Structural and Functional Characteristics of Greenhouses in European Union Countries: Part I, Design Requirements. *Journal of Agricultural Engineering Research 75(1),* pp. 1-16. 2000.

[12] B. Cemek and Y. Demir . Testing of the Condensation Characteristics and Light Transmissions of Different Plastic Film Covering Materials. *Polymer Testing 24(3),* pp. 284-289. 2005.

[13] F. Geoola, Y. Kashti and U. M. Peiper . A Model Greenhouse for Testing the Role of Condensation, Dust and Dirt on the Solar Radiation Transmissivity of Greenhouse Cladding Materials. *Journal of Agricultural Engineering Research 71(4),* pp. 339-346. 1998.

[14] D. Ciolkosz . Design Daylight Availability for Greenhouses using Supplementary Lighting. *Biosystems Engineering 100(4),* pp. 571-580. 2008.

[15] M. Doriais, "The Use of Supplemental Lighting for Vegetable Crop Production: Light Intensity, Crop Response, Nutrition, Crop Management" Cultural Practices, 2003.

[16] Y. Zhang, L. Gauthier, D. Halleux, B. Dansereau and A. Gosselin. Effect of Covering Materials on Energy Consumption and Greenhouse Microclimate. *Agricultural and Forest Meteorology. 82(1-4),* pp. 227. 1996.

[17] T. Bartzanas, M. Tchamitchian and C. Kittas. Influence of the Heating Method on Greenhouse Microclimate and Energy Consumption. *Biosystems Engineering 91(4),* pp. 487-499. 2005.

[18] M. C. Sanchez-Guerrero, P. Lorenzo, E. Medrano, N. Castilla, T. Soriano and A. Baille. Effect of Variable CO_2 Enrichment on Greenhouse Production in Mild Winter Climates. *Agricultural and Forest Meteorology 132(3-4),* pp. 244-252. 2005.

[19] Z. S. Chalabi, A. Biro, B. J. Bailey, D. P. Aikman and K. E. Cockshull. SE—Structures and Environment:Optimal Control Strategies for Carbon dioxide Enrichment in Greenhouse Tomato Crops—Part 1: Using Pure Carbon dioxide. *Biosystems Engineering 81(4),* pp. 421-431. 2002.

[20] "World Oil Markets," Energy Information Administration, United States, 2006.

[21] "Biomass and Feedstocks for Bio-energy and Bioproducts Industry : The Technical Feasibility of a Billion-ton A View of 17 Studies. *Biomass Bioenergy 25(1),* pp. 1-28. 2003.

[24] Food and Agriculture Organization of the United Nations., Stockholm Environment Institute.,. *What Wood Fuels can do to Mitigate Climate Change*.2010.

[25] "Fossil Fuel to Products," The National Energy Educational Development Project, VA, United States of America, 2012-2013.

[26] J. Sandeman. Feed ‑ In Tariffs: Accelerating the Deployment of Renewable Energy. *Int. J. Environ. Stud. 67(3),* pp. 463-463. 2010. Available: http://dx.doi.org.ezproxy.library.dal.ca/10.1080/00207230701737011.

[27] K. Blok. Renewable Energy Policies in the European Union. *Energy Policy 34(3),* pp. 251-255. 2006.

[28] "Global Wood Pellet Markets and Industry: Policy, Drivers, Market Status and Raw Material Potential," IEA BioEnergy, 2007.

[29] L. Nikolaisen, M. Junginger, C. Goh.S, J. Heinimo, D. Bradley, R. Hess and J. Jacobson, "Global Wood Pellet Industry Market and Trade Study," IEA Bioenergy Task 40 "Sustainable Bioenergy Trade", 2011.

[30] "Wood Pellet Association of Canada; Wood Pellet Production: Raw Material," vol. 2013, 2012.

[31] M. M. Roy, A. Dutta and K. Corscadden. An Experimental Study of Combustion and Emissions of Biomass Pellets in a Prototype Pellet Furnace. *Appl. Energy 108(0),* pp. 298-307. 2013.

[32] R. Samson, S. Mani, R. Boddey, S. Sokhansanj, D. Quesada, S. Urquiaga, V. Reis and C. Ho Lem. The Potential of C4 Perennial Grasses for Developing a Global BIOHEAT Industry. *Crit. Rev. Plant Sci. 24(5-6),* pp. 461-495. 2005. Available: http://dx.doi.org.ezproxy.library.dal.ca/10.1080/07352680500316508.

[33] S. J. Bouman O.T. . Biomass allocation and photosynthetic capacity of willow (salix spp.) bio-energy varieties. *Forstarch.Forstarchiv 83(4),* pp. 139-143. 2012.

[34] D. Kauter, I. Lewandowski and W. Claupein. Quantity and quality of harvestable biomass from populus short rotation coppice for solid fuel use-a review of the physiological basis and management influences. *Biomass & Bioenergy. 24(6),* pp. 411-427. 2003.

[35] "Grass energy: Basics of production, processing, and combustion of grasses for energy 2009" Biomass Energy Resource Center, 2011.

[36] McKendry P. Energy production from biomass (part 1): Overview of biomass. *Bioresour. Technol. 83(1),* pp. 37-46. 2002.

[37] J. Swithenbank, Q. Chen, X. Zhang, V. Sharifi and M. Pourkashanian. Wood would burn. *Biomass Bioenergy 35(3),* pp. 999-1007. 2011.

[38] M. Stahl, K. Granström, J. Berghel and R. Renström. Industrial processes for biomass drying and their effects on the quality properties of wood pellets. *Biomass Bioenergy 27(6),* pp. 621-628. 2004.

[39] D. S. Timmons . Estimating a Technically Feasible Switch Grass Supply Function: A Western Massachusetts Example. *BioEnergy Research 5(1),* pp. 236-246. 2012.

[40] S. Mani, S. Sokhansanj, X. Bi and A. Turhollow. Economics of Producing Fuel Pellets from Biomass Electronic Resource. *22(3),* pp. 421-426. 2006.

[41] H. P. Michelsen, F. Frandsen, K. Dam-Johansen and O. H. Larsen. Deposition and High Temperature Corrosion in a 10 MW Straw Fired Boiler. *Fuel Process Technol 54(1-3),* pp. 95-108. 1998. Available: http://dx.doi.org/10.1016/S0378-3820(97)00062-3.

[42] C. Nielsen, M. Larsen, V. Nielsen, U. Zielke, J. K. Kristensen and B. H. Christensen, "Straw for energy production" The Centre for Biomass Technology, Cophenhagen, Tech. Rep. 2, 1998.

[43] R. Herendeen and S. Brown. A Comparative Analysis of Net Energy from Woody Biomass. *Energy 12(1),* pp. 75-84. 1987.

[44] L. G. Angelini, L. Ceccarini and E. Bonari. Biomass Yield and Energy Balance of Giant Reed (arundo donax L.) Cropped in Central Italy as Related to Different Management Practices. *Eur. J. Agron. 22(4),* pp. 375-389. 2005.

[45] C. Schmidl, M. Luisser, E. Padouvas, L. Lasselsberger, M. Rzaca, C. Ramirez-Santa Cruz, M. Handler, G. Peng, H. Bauer and H. Puxbaum. Particulate and Gaseous

Emissions from Manually and Automatically Fired Small Scale Combustion Systems. *Atmos. Environ. 45(39),* pp. 7443-7454. 2011. Available: http://ezproxy.library.dal.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=67113393&site=ehost-live.

[46] B. M. Jenkins, L. L. Baxter and T. R. Miles. Combustion Properties of Biomass. *Fuel Process Technol 54(1),* pp. 17-46. 1998.

[47] J. M. Johansen, J. G. Jakobsen, F. J. Frandsen and P. Glarborg. Release of K, Cl, and S during Pyrolysis and Combustion of High-Chlorine Biomass. *Energy and Fuels 25(11),* pp. 4961-4971. 2011. Available: http://dx.doi.org/10.1021/ef201098n.

[48] G. Shen, S. Tao, S. Wei, Y. Zhang, R. Wang, B. Wang, W. Li, H. Shen, Y. Huang, Y. Chen, H. Chen, Y. Yang, W. Wang, W. Wei, X. Wang, W. Liu, X. Wang and S. L. M. Simonich. Reductions in Emissions of Carbonaceous Particulate Matter and Polycyclic Aromatic Hydrocarbons from Combustion of Biomass Pellets in Comparison with Raw Fuel Burning. *Environmental Science and Technology 46(11),* pp. 6409-6416. 2012. Available: http://dx.doi.org/10.1021/es300369d.

[49] C. L'Orange, J. Volckens and M. DeFoort. Influence of Stove Type and Cooking Pot Temperature on Particulate Matter Emissions from Biomass Cook Stoves. *Energy for Sustainable Development 16(4),* pp. 448-455. 2012.

[50] C. Davidson, R. Phalen and P. Solomon. Airborne Particulate Matter and Human Health: A review. *Aerosol. Sci. Technol. 39(8),* pp. 737-749. 2005. Available:

http://search.proquest.com.ezproxy.library.dal.ca/docview/17216659?accountid=10406.

[51] E. Gustafsson, L. Lin and M. Strand. Characterization of Particulate Matter in the Hot Product Gas from Atmospheric Fluidized Bed Biomass Gasifiers. *Biomass Bioenergy 35*pp. S71-S78. 2011. Available: http://dx.doi.org/10.1016/j.biombioe.2011.02.053.

[52] L. S. Johansson, C. Tullin, B. Leckner and P. Sjovall. Particle Emissions from Biomass Combustion in Small Combustors. *Biomass Bioenergy 25(4),* pp. 435-446. 2003. Available: http://dx.doi.org/10.1016/S0961-9534(03)00036-9.

[53] L. S. Bäfver, B. Leckner, C. Tullin and M. Berntsen. Particle Emissions from Pellets Stoves and Modern and Old-type Wood Stoves. *Biomass Bioenergy 35(8),* pp. 3648-3655. 2011.

[54] P. Dare, J. Gifford, R. J. Hooper, A. H. Clemens, L. F. Damiano, D. Gong and T. W. Matheson. Combustion Performance of Biomass Residue and Purpose Grown Species. *Biomass Bioenergy 21(4),* pp. 277-287. 2001.

[55] S. Paulrud and C. Nilsson. Briquetting and Combustion of Spring-Harvested Reed Canary-Grass: Effect of Fuel Composition. *Biomass Bioenergy 20(1),* pp. 25-35. 2001.

[56] J. F. González, C. M. González-García, A. Ramiro, J. González, E. Sabio, J. Gañán and M. A. Rodríguez. Combustion Optimisation of Biomass Residue Pellets for

Domestic Heating with a Mural Boiler. *Biomass Bioenergy 27(2),* pp. 145-154. 2004.

[57] J. F. González, C. M. González-García, A. Ramiro, J. Gañán, J. González, E. Sabio, S. Román and J. Turegano. Use of Almond Residues for Domestic Heating. Study of the Combustion Parameters in a Mural Boiler. *Fuel Process Technol 86(12–13),* pp. 1351-1368. 2005.

[58] J. F. González, C. M. González-García, A. Ramiro, J. Gañán, A. Ayuso and J. Turegano. Use of Energy Crops for Domestic Heating with a Mural Boiler. *Fuel Process Technol 87(8),* pp. 717-726. 2006.

[59] T. Nussbaumer . Combustion and Co-combustion of Biomass: Fundamentals, Technologies, and Primary Measures for Emission Reduction. *Energy & Fuels: An American Chemical Society Journal. 17(6),* pp. 1510. 2003.

[60] L. S. Johansson, B. Leckner, L. Gustavsson, D. Cooper, C. Tullin and A. Potter. Emission Characteristics of Modern and Old-type Residential Boilers Fired with Wood Logs and Wood Pellets. *Atmos. Environ. 38(25),* pp. 4183-4195. 2004.

[61] D. Eskilsson, M. Rönnbäck, J. Samuelsson and C. Tullin . Optimisation of Efficiency and Emissions in Pellet Burners. *Biomass and Bioenergy Biomass and Bioenergy 27(6),* pp. 541-546. 2004.

[62] V. K. Verma, S. Bram, G. Gauthier and J. De Ruyck. Performance of a Domestic Pellet Boiler as a Function of Operational Loads: Part-2. *Biomass Bioenergy 35(1),* pp. 272-279. 2011.

[63] V. K. Verma, S. Bram, F. Delattin, P. Laha, I. Vandendael, A. Hubin and J. De Ruyck. Agro-pellets for Domestic Heating Boilers: Standard Laboratory and Real Life Performance. *Appl. Energy 90(1),* pp. 17-23. 2012.

[64] Z. Liu, X. Liu, B. Fei, Z. Jiang, Z. Cai and Y. Yu. The Properties of Pellets from Mixing Bamboo and Rice Straw. *Renewable Energy 55(0),* pp. 1-5. 2013.

[65] G. A. Holt, T. L. Blodgett and F. S. Nakayama. Physical and Combustion Characteristics of Pellet Fuel from Cotton Gin by-Products Produced by Select Processing Treatments. *Industrial Crops and Products 24(3),* pp. 204-213. 2006.

[66] A. Vadiee and V. Martin. Energy Management in Horticultural Applications through the Closed Greenhouse Concept, State of the Art. *Renewable and Sustainable Energy Reviews 16(7),* pp. 5087-5100. 2012.

Table 15. Inventory data collected during initial visits. It presents general information on greenhouse size, months of operation, infrastructural information, lighting, heating, CO_2 injection, irrigation, cooling and ventilation (continued).

Greenhouse	Greenhouse 1	Greenhouse 2	Greenhouse 3	Greenhouse 4	Greenhouse 5	Greenhouse 6	Greenhouse 7	Greenhouse 8	Greenhouse 9	Greenhouse 10
Area, Sq.ft	27876	20778	38880	11520	97152	374200	14000	16750	130680	32000
Months of Operation	Mar - Aug	Feb - Aug	Mar - Oct	Apr-Jul	Year round	Year round	Feb-Oct	Mar-Oct	Year round	Year round
Products	Potted plants	Potter Plants	Vegetables	Vegetable transplants	Vegetables	Potted plants and cut-flowers	Vegetables	Potted plants	Vegetables	Potted plants
Style	Free standing	Free	Gutter connected	Free standing	Gutter connected	Gutter connected	Free standing	Free standing	Gutter connected	Gutter connected
Glazing	Double poly	Inflated double poly	Inflated double poly	Inflated double poly	Polycarbonate and inflated double poly	Inflated double poly and glass	Inflated double poly	Inflated double poly	Glass and Inflated double poly	Retractable, glass and double poly
Supplemenary Lighting	No	In Nursery only	In Nursery only	No	In Nursery only	For Nursery & cut flower	No	No	In Nursery only	In Nursery only

Table 1 (Continued).

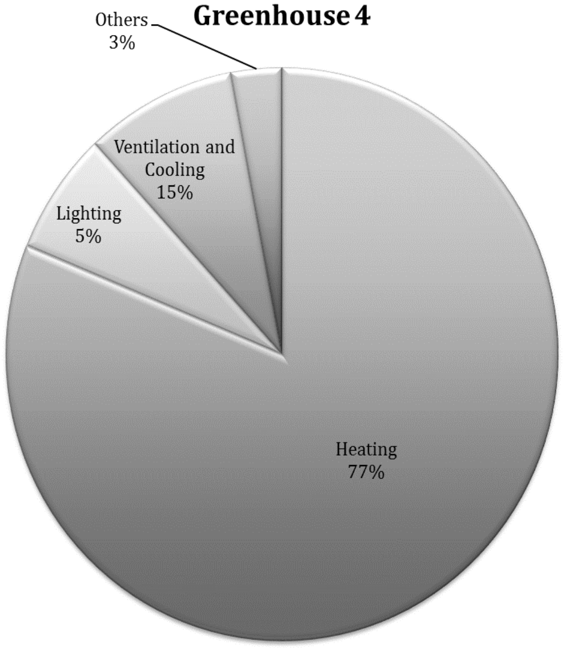
Greenhouse	Greenhouse 1	Greenhouse 2	Greenhouse 3	Greenhouse 4	Greenhouse 5	Greenhouse 6	Greenhouse 7	Greenhouse 8	Greenhouse 9	Greenhouse 10
Heating	Furnace oil Boilers	Pelco pellet boiler and Furnace Oil Boiler	Decker's Boiler and Furnace oil boilers	Furnace Oil Boilers	Furnace oil Boilers	Wood Chip boiler + 2 Furnace oil boilers	Central furnace oil boiler	Oil fired furnace	Imported wood chip boiler	Deckers boiler (premium wood pellets)
Heating system	Individual heating (Air)	Central and Individual Furnace oil Boiler (Hot water)	Central +individual furnace oil boilers (Hot Water)	Individual furnace oil boilers (Air)	Central Furnace Oil boilers (Hot Water & Pipe heating)	Central Wood and furnace oil boilers (Steam)	Furnace oil (Steam)	Individual (Air)	Central heating (hot water)	Central heating (Hot water)
Cooling and Ventilation	Side wall roll up + Rarely used exhaust fans	Exhaust fans only	Exhaust fans only	Exhaust fans + Side wall roll up	Ridge ventilation and exhaust fans	Side wall role up, exhaust fans, roof ventilation	Exhaust fan only	Exhaust fans only	Cooling and Ventilation	Side wall roll up + Rarely used exhaust fans

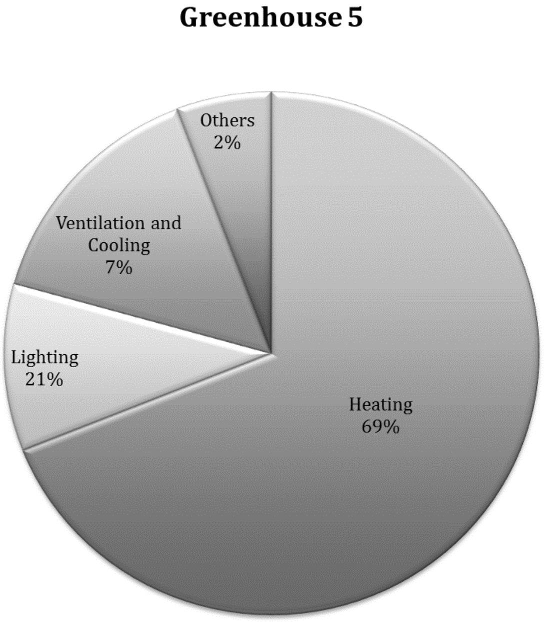
Table 1 (Concluded).

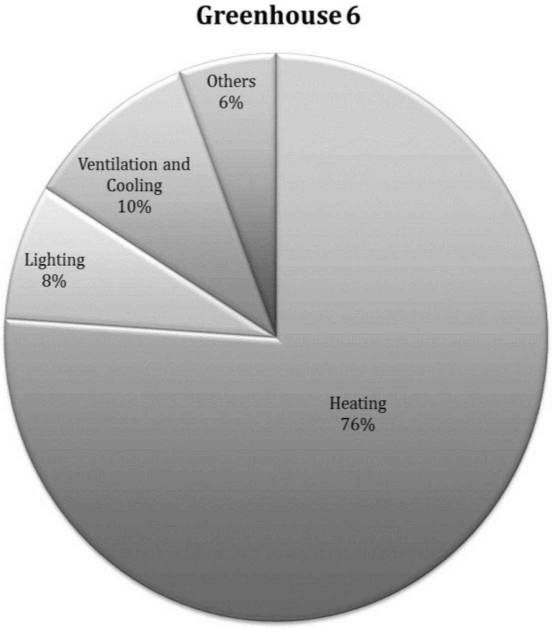
Greenhouse	Greenhouse 1	Greenhouse 2	Greenhouse 3	Greenhouse 4	Greenhouse 5	Greenhouse 6	Greenhouse 7	Greenhouse 8	Greenhouse 9	Greenhouse 10
CO_2 injection	No	No	Yes	No	Yes	Yes	No	No	Yes	Yes
Irrigation	Ebb and Flood	Over head sprinklers and Hand watering	Drip Irrigation	Hand watering	Drip Irrigation	Hand Watering & Overhead sprinklers	Drip and Hand watering	Drip and Hand watering	Drip irrigation	Over head sprinklers and hand watering

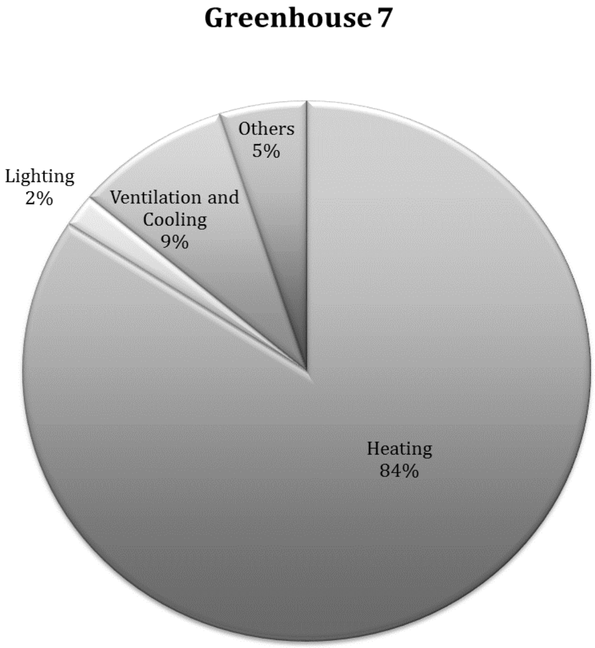
APPENDIX B

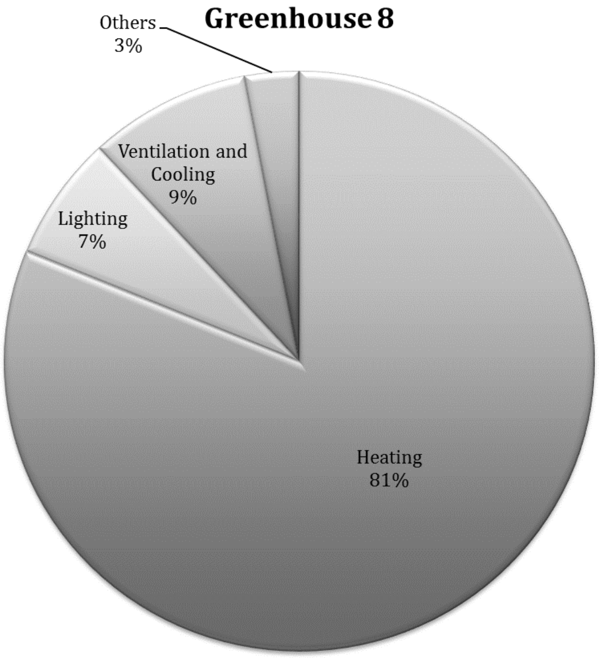
Energy Cost Breakdown


Greenhouse 4


Greenhouse 5


Greenhouse 6
Others
6%
Ventilation and
Cooling
10%
Lighting
8%
Heating
76%


Greenhouse 7
Others
5%
Lighting
2%
Ventilation and
Cooling
9%
Heating
84%


Greenhouse 8
Others
3%
Ventilation and
Cooling
9%
Lighting
7%
Heating
81%

APPENDIX C

Copyright Permission Letter:

July 27, 2013

Journal of Sustainable Bioenergy Systems
Scientific Research Publishing Inc.
P.O. Box 54821
Irvine CA 92619-4821 – USA

Dear Editor,

I am preparing my M.Sc thesis for submission to the Faculty of Graduate Studies at Dalhousie University, Halifax, Nova Scotia, Canada. I am seeking your permission to include a manuscript version of the following accept paper as a chapter in the thesis:

Controlled Batch Leaching Conditions for Optimal Upgrading of Agricultural Biomass. (Paper ID: 2210067, Status as on July 27, 2013 – Paper Typesetting).

Canadian graduate theses are reproduced by the Library and Archives of Canada (formerly National Library of Canada) through a non-executive, world-wide license to reproduce, loan, distribute, or sell theses. I am also seeking your permission for the material described above to be reproduces and distributed by the LAC (NLC). Further details about the LAC (NLC) thesis program are available on the LAC(NLC) website (www.nlc-bnc.ca).

Full publication details and a copy of this permission letter will be included in the thesis.

Yours sincerely,

Prabahar Ravichandran

Permission is granted for:

The inclusion of the material described above in your thesis.
For the material described above to be included in the copy of your thesis that is sent to the Library and Archives of Canada (formerly National Library of Canada) for reproduction and distribution.

Name: Ray Wang
Title: Editorial Assistant

Signature:
Date: 8 June, 2013