Production of High pH Value Bio-oil from Woody Biomass and Poultry Litter

by

Harideepan Ravindran

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Approved by

Sushil Adhikari, Co-chair, Assistant Professor of Biosystems Engineering
Lewis Payton, Co-chair, Associate Research Professor of Mechanical Engineering
Robert L. Jackson, Associate Professor of Mechanical Engineering

Abstract

Fast pyrolysis, a biomass to liquid conversion process, has attracted a lot of interest from industry and academia due to its high oil yield. Bio-oil can be produced from various biomass feedstocks that are regionally appropriate. Small diameter trees removed from forests have very little economic value in the current market, and the utilization of underutilized biomass to bio-oil could be a niche market for energy production. Also, Alabama is the third largest poultry producing state, and has substantial amount of poultry litter available. The main objective of this work was to produce high pH value bio-oil using cheap and simple methods. Apparently, this study was divided into three specific objectives in which the first task focused on determining maximum bio-oil production from selected biomass and their pH value. The second and third tasks comprised of experimentation and evaluation of new techniques to produce high pH value bio-oil.

The first task evaluated bio-oil production from pine wood, underutilized forest biomass, and poultry litter at different temperatures in between 425-500^{o}C, and characterized according to the ASTM Standard (D7544-09) to document the effect of temperatures. The study found that pine wood gave the highest bio-oil at 500^{o}C, but the poultry litter bio-oil showed the highest pH. In the second and third tasks, cheap and simple methods, such as using a bio-based additive (poultry litter) with primary biomass (pine wood), and through cascade (2- stage) pyrolysis process, were used to produce high pH value bio-oil. From the studies, it was found that the pH value of bio-oil increases while increasing the composition of the additive in the primary

biomass. However, the bio-oil produced from 15 wt.% poultry litter in pine wood did not meet selected properties recommended by the ASTM Standard. Further, the pH value of bio-oil obtained from 2-stage process was slightly higher when compared to the bio-oil produced from single stage process. Here, style of references used in the journal “Bioresource Technology” was followed in this report.

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CHAPTER 1

INTRODUCTION

Pyrolysis is an ancient technology used by Egyptians in tar production for caulking boats and in making certain embalming agents. Since mid 1970s, inevitable demand on energy pushed the researchers and scientists to explore renewable source of energy to meet the future demand. Later, in 1980s, they found that high yield of pyrolysis liquid (bio-oil) can be produced through a fast pyrolysis technique. Here, biomass is used as the input and the products obtained from this process can be used as an energy source or as a feedstock for chemical production. Fast pyrolysis is a thermo-chemical process where biomass feedstock is heated rapidly in the absence of oxygen to produce vapors, aerosols and gases, and these elements are condensed rapidly into a liquid called bio-oil. The major products of the fast pyrolysis process are char (solid), bio-oil (liquid) and gases.

Fast pyrolysis process has different advantages such as flexibility in using different biomass feedstock, high bio-oil production and easy transportation (denser liquid). Bio-oil produced from fast pyrolysis process has numerous applications in combustion, heat and electricity production, transportation fuels, chemicals and in food industry. Though bio-oil has wide applications, its negative properties such as acidity, high oxygen content, thermal instability and storage problems play a significant role in restricting its market value. Among these drawbacks, acidity of the bio-oil is the most influential feature as it limits most of the applications of the product (bio-oil).

An auger reactor was developed at Auburn University to carry out the fast pyrolysis process, and the simplified model of the reactor is shown in the Figure 1. Here, biomass is feed into the hot screw conveyor/ auger reactor (heaters are provided to heat the periphery of the conveyor) to heat the biomass. Screw conveyor consists of a screw (auger) and a reactor pipe (to support the screw and guide the biomass). A motor was installed to drive the screw conveyor, and as the auger moves inside the reactor pipe, the biomass advances to the hot zone of the reactor to absorb the heat and produces gaseous elements (vapors, aerosols and gases) and char (collected at the end of the system). These gaseous elements are passed through the heat exchanger (condensers) to condense the fumes into bio-oil and the non condensable gases (NCG) were vented.

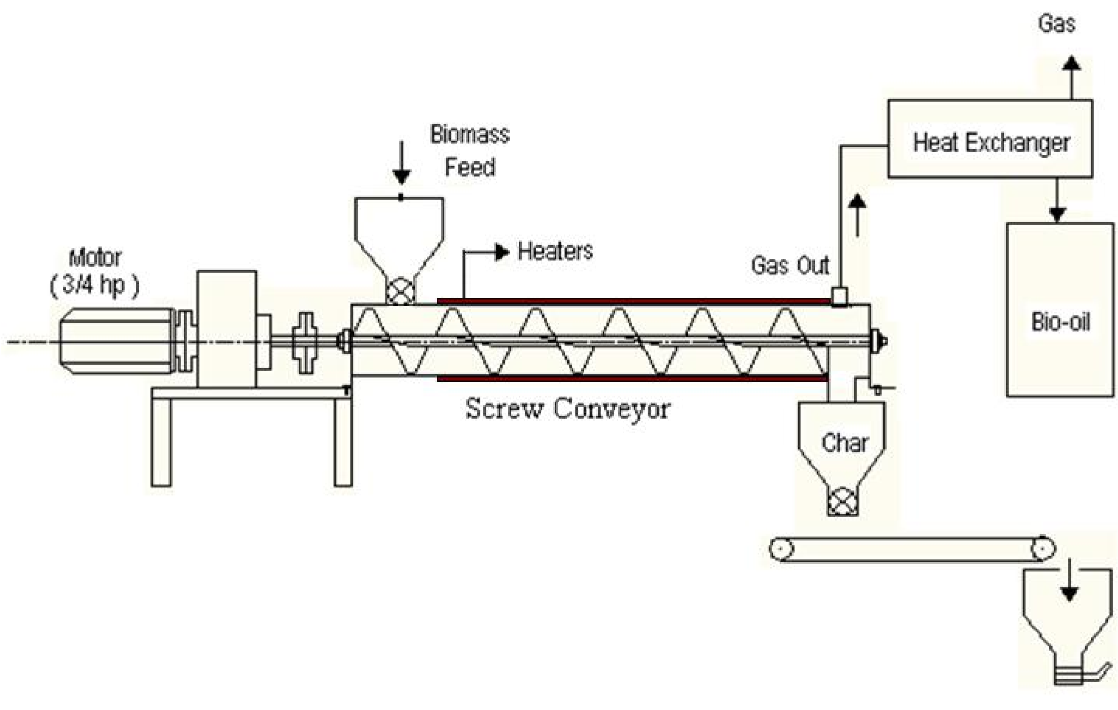

Figure 1: Simplified model of an auger reactor at Auburn University.

CHAPTER 2

SCOPE AND OBJECTIVES

Since application of bio-oil are limited by its negative attributes, in this work, acidity of the bio-oil was considered as the major drawback and a few simple techniques were implemented on the fast pyrolysis process to remove or reduce the acidity in the oil. The main goal of this research was to increase the pH of bio-oil so that it can be used in existing refineries with no or minimum upgrading. The specific objectives of this project were as follows:

1. Production of bio-oil from selected biomass feedstocks

   Bio-oils were produced from selected feedstocks (at different operating temperatures) and their physical properties were determined. Later, optimum temperature for maximum bio-oil production and their respective pH value were determined for each biomass type.

2. Production of bio-oil using sacrificial bio-based additive

   Bio-oils were produced after mixing two different biomass (in which poultry litter acts as an additive) to increase its pH value. Operating temperature and primary biomass would be selected from the previous objective and verifying the technique by comparing the pH value obtained.

3. Production of bio-oil using cascade pyrolysis reactors

   Implementing of 2-stage process for bio-oil production and validating the technique by comparing its results (pH value) with the first objective. Operating parameters will be selected from the first objective.

CHAPTER 3

LITERATURE REVIEW

This chapter comprises a comprehensive outline on world's current energy availability, energy production and new accessible energy options to meet the upcoming demand. A brief review on future energy demand, factors affecting the demand and the need for exploring new and alternate energy resources (bio-energy) were also discussed here. Further, various technologies involved in bio-energy production and factors involved in selecting the required technology (pyrolysis) to produce expected form of bio-energy (interest of this study) were detailed. As the selected technology has different methods/processes, all the methods involved in this technology were reviewed, and the best method (fast pyrolysis) was selected as per the requirement of this study. It also includes the features and factors influencing the process, and the reactors (including the reactor selection, auger reactor) involved in bio-oil production were also presented. Major form of bio-energy (bio-oil) obtained from this process was focused, and its various features such as properties, applications and challenges were also discussed below. In addition, a brief economic analysis on the method selected for this study was also presented in this section.

3.1 ENERGY AND ITS DEMAND

In this vast universe, every system requires some form of energy to trigger itself to execute some kind of work. Currently, numerous tools are been being created by humans to simplify and carry out their deed easily. These tools consume various modes of energy (like electricity, natural gas, liquid fuels, coal, nuclear and other renewable resources) to perform its actions. Basically, utilization of these energy resources (stated above) can be characterized under four different sectors such as transportation, industrial, commercial and residential. Since 1990's, the amount of energy consumed by these sectors is growing up and this trend line is expected to rise in the future because of the demand created by the growing population, surplus investment on technologies for improvising the casual amenities, and improper utilization of the available energy. Certainly, international energy outlook 2010 illustrated that (Figure 2), the world marketed energy consumption will be expanded by 49% between 2007 and 2035 [1]. However, annual energy outlook 2010 showed that (Figure 3) in the U.S., the total primary energy consumption is expected to increase by 14% from 2008 to 2035 with an average annual growth rate of 0.5 % [2].

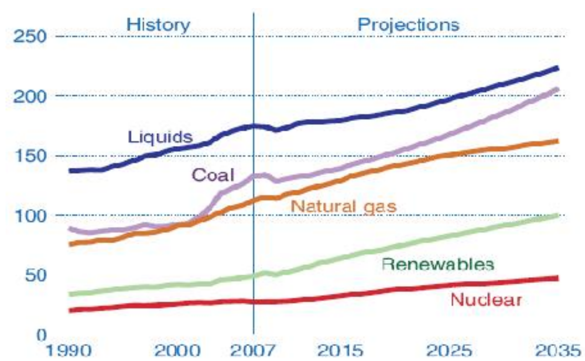

Figure 2: World marketed energy consumption (quadrillion Btu) by fuel type [1] .

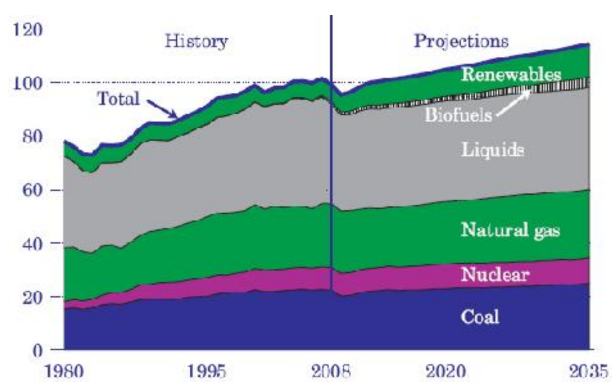

Figure 3: U.S. primary energy consumption (quadrillion Btu) by fuel type [2].

From Figures 2 and 3, it was evident that the demand of energy will be elevating for the next 25 years, and the growing consumption of fossil fuels were high in-spite of its increasing price and depleting resources. Though a fall in natural gas consumption (Figure 3) exists during 2008 to 2014 (1.5% per year), it gets elevated and shows an overall growth rate of 0.2% per year from 2008 to 2035. Nevertheless, the consumption of coal increases by 0.4% per year. The Energy Information Administration (EIA) states that renewable fuels will be used to generate electricity and liquid fuels from various renewable resources for the transportation sector [2].

Certainly, Figure 3 shows that the amount of fossil fuel usage in total energy drops from 84% to 78% (2008-2035) and the share of renewable energy in total energy increases from 8% to 14% (2008-2035) [2]. In addition, various government policies and state programs were implemented to increase the production of renewable energy resources, and The American Recovery and Reinvestment Act of 2009 offers federal funding, tax credits and loan guarantees to encourage financial outlay in energy efficiency and renewable energy.

3.2 NEED FOR ALTERNATIVE ENERGY RESOURCES

In this modern world, energy has never been an option; it’s the key to access our basic amenities. The present situation demands a clean, reliable, and steady supply of energy to meet our basic comfort (residential), commercial, transportation, and industrial usage. In which, energy used by industries is relatively higher than the other three sectors, and nearly 68% of the energy consumed by industries is from liquid fuels and natural gas, whereas the remaining 32% is from electricity, coal and renewable [2]. However, the availability of fossil fuels are no longer sufficient to meet our future energy demand, and resulting in various tribulations such as price rise, energy security and serious concerns on climate change which resulted in multiplying the interest on alternative energy. This pushes both scientists and policy makers to direct their search towards alternative (clean energy) and renewable energy resources to avoid obnoxious situation on energy demand in the future.

Currently, various expansions are being carried out in the field of alternative energy and in particular, solar energy is considered as a primary source of energy available in this world as it is obtained directly from the radiation of sun. It is one among the noticeable clean renewable energy resource. During clear sky, direct sun light can produce a radiation of 1000 W/m^2 on a plain horizontal surface. In the U.S. (considering 48 states), the production of total amount of solar energy is about 13.5 $x10^{15}$ kWh per year, and at present 23.2 $x10^9$ kWh per year is being produced as electricity through solar thermal energy [3]. However, solar energy is not highly established because of its various negative attributes such as poor conversion efficiency (from light energy to electric energy), variation of light during the day, weather conditions and seasonal changes.

Apart from solar energy, there are other alternative renewable energy technologies assisting to meet the future energy demand such as wind, water, geothermal and biofuels (products derived from biomass). The technology on these energy resources can be enhanced to produce a significant amount of resources to back the fossil fuel requirement. On the other hand, in U.S., biomass and biomass derived gases have supplied nearly 55,000 GWh of electricity (in 2006) and provided feedstock for about 6.5 billion gallons of ethanol in 2007 [4].

3.3 BIOMASS, AN ALTERNATIVE ENERGY AND ITS AVAILABILITY

Certainly, exploration on alternative energy resources are encouraged to alleviate this situation as these resources are said to be renewable, ease with environment, and global climate change. Particularly, biomass stands ahead of many alternatives by hauling the nation's attention towards it. Biomass can be converted to bio-fuels through various techniques, and they can be used significantly to reduce the dependence on petroleum products.

Environmental concerns, national energy security and climate change are the primary reasons to explore alternative energy resources. Significant amount of resources has been devoted in producing transportation fuels from biomass and other sources. The Billion-Ton study estimated that approximately 1.3 billion dry tons of biomass is available annually in U. S. and if all the biomass are used to produce ethanol, then it has the potential to produce up to 60 billion gallons [5]. These facts motivated both academia and industries on bio-energy (energy derived from biomass) particularly on converting the biomass to liquid fuels through thermochemical or biochemical processes. Within the various thermochemical processes, fast pyrolysis process has attracted a lot of interest because of its high liquid fuel (bio-oil) production and its feedstock flexibility. The two major products from the fast pyrolysis process are bio-oil and bio-char (solid left after pyrolysis), in which the bio-oil is the major product of this process that can be stored and transported, and the bio-char can be utilized as soil amendment or carbon sequestration.

Biomass is required to produce bio-energy either in liquid, solid or gases form and recently, in U.S. an analysis was made over the availability of biomass from various sources such as forestry and agricultural residues. It states that U.S has a capacity to produce a billion ton of biomass every year, which includes 368 million dry tons/year of forestry residues. Further, forest residues include 64 million dry tons/year of logging and other residues. The biomass obtained from forest thinning and clearing operation has little or no value, and also has no other methods to process such biomass, except pyrolysis [5].

The term biomass represents all living and recently living biological organisms found in our planet or in other words, all organic matter derived from plants and plant based wastes are called biomass. Basically sun is the prime source of energy from which the plants produce their own food through photosynthesis process (where the solar energy is converted into chemical energy in the plant material) to develop themselves. This chemical energy (stored in biomass) can be extracted (as another form of energy) by various energy conversion processes such as thermochemical and bio-chemical processes. Certainly, this type of resource is considered as a renewable source for energy production because it is available in nature and found enormously. However, fossil fuels are obtained from organic matter (after the influence of geological process) and they are not adjudged as a renewable source of energy because of the time taken by the process to convert the biomass into coal or petroleum based products.

Over the last few years, several discussions were being made on energy security and exploration of alternative energy resources to support the future demand on energy. Since 1990, hunt on renewable resources for energy production has shown a growing trend particularly towards using biomass as an energy source. The rationales behind the attraction on biomass are, ability to produce biomass (most of the countries in the world has a capability to generate biomass, especially, western Europe and US are producing food surplus), technological developments in both energy conversion techniques and in crop production, proficiency in achieving higher conversion efficiency, rural economic development, low cost fuel production, petroleum displacement, fossil fuel displacement, reduced greenhouse gas emissions, and improved soil fertility and agricultural ecology [6-7].

Basically, biomass is available from different sources in different ways, and typically they are distinguished in four eminent forms such as woody plants, herbaceous plants/grasses, aquatic plants and manures [8]. However, the major constituents of these biomasses are cellulose (40-50% by dry weight), hemicellulose (20-40% by dry weight) and lignin (20-40% by dry weight in woody plants and 10-40% by dry weight in herbaceous plants), An ideal energy crop should hold the following characteristic features to achieve successful commercial energy forming [7] and they are:

- high yield (maximum production of dry matter per hectare)
- low energy input to produce
- low production cost
- low nutrient requirements
- composed of least adulterants

In addition, moisture content present in biomass plays a very important role in selecting the energy conversion process. Biomass with low moisture content (woodchips) is treated in dry conversion processes such as gasification, pyrolysis and combustion; whereas, high moisture content biomass is used in wet or aqueous conversion process such as fermentation.

3.4 BIO-ENERGY PRODUCTION TECHNOLOGIES

Generally, future demand on energy drives both the developed and developing countries towards alternative (clean) or renewable energy producing technologies [3], and biomass is considered as a potential source from which various forms of energy can be produced. Currently, several bio-energy (biomass to energy) conversion technologies are available to convert the biomass to heat, power and liquid fuels [9] and such technologies are broadly classified into three types. Figure 4 shown below represents the major classification of bio-energy conversion technologies.

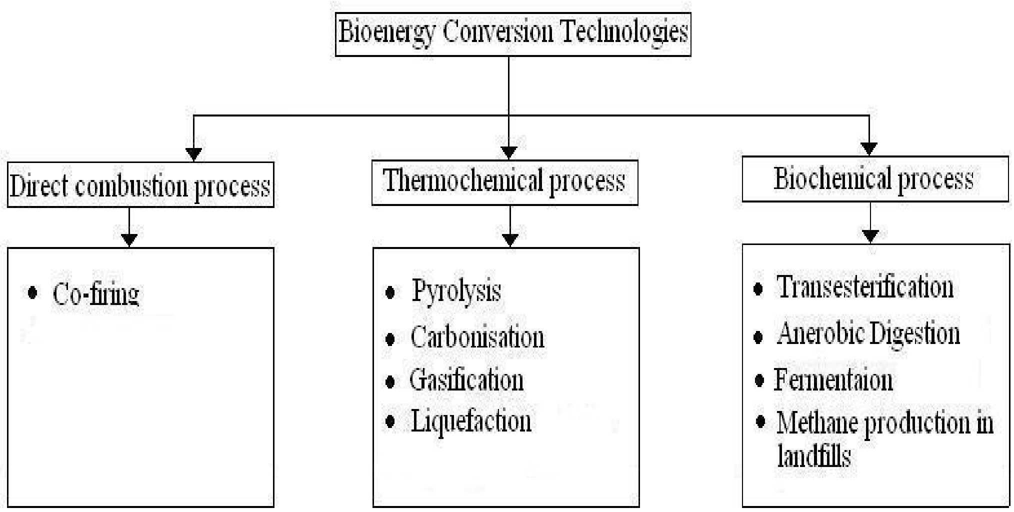

Figure 4: Bio-energy conversion technology [10-11].

However, the technologies mentioned above are implemented to produce bioenergy, and each technique requires unique form of biomass to carry out the process. In this work, we are interested in processing dry woody biomass and animal manure (poultry litter) because of the availability of such feedstocks are abundant in this region (AL, USA). The following technologies are being encouraged to process these biomasses in order to produce bio-energy and they are:

- Co-firing
- Pyrolysis
- Carbonation
- Gasification
- Liquefaction

3.4.1 CO-FIRING

It is a direct combustion process in which fossil fuels are co-fired with low cost biomass residues (in the presence of air) to convert chemical energy stored in biomass to heat or produce steam. Generally, the process is carried out around 800-1000°C and the equipment such as stoves, boilers, furnaces, steam turbines and turbo generators are used to achieve the process [11]. Various feedstocks (with moisture content < 10 wt. %) such as wood chips, sawdust, bark, hog fuel, black liquor, bagasse, straw, municipal solid waste (MSW), and wastes from the food industry are being used for this process [10-12]. This process has a wide application, particularly in electricity generation. The advantages of this process are low sulfur, nitrogen (relative to coal) and net CO_2 emission levels (almost zero) in the fuels and in addition to that residues can be used effectively in power production [10]. However, inefficient use of the limited life-time equipment, pretreatment associated with financial costs and lack of year round production in electricity limits the application of this process [10, 12].

3.4.2 PYROLYSIS

It is a thermochemical process where the biomass is heated in the absence of oxygen at moderate to high temperatures (about 350-700°C) to produce liquid (bio-oil), char and gases [11-14]. This process is flexible to various kinds of feedstocks such as pinewood, forest residues, switchgrass, poultry litter, peanut hulls, sawdust, plastics and rubber [15-23] . The products obtained from this technique have a wide range of applications in power generation with liquids, combustion, chemical production and many more [13].

3.4.3 CARBONATION

Carbonation is an old age pyrolytic process where the volatile compounds of the biomass are removed by heating it under the absence of oxygen to produce charcoal. This process is also called as torrefaction or dry wood distillation, and the biomass used for this process are wood, reed canary grass, willow and many more [10, 24-25]. Generally, the operating temperature followed to achieve this process is about 200-300°C, and this technology has numerous applications in industrial, commercial and domestic sectors [10, 24-25].

3.4.4 LIQUEFACTION

It is a technique used to produce clean liquids (bio-oil) from biomass in the presence of a solvent or additive at moderate to high temperatures (250–550°C) and pressures (5–25 MPa) [10, 26]. This thermochemical process is carried out under wet conditions and the biomass used in the process are wood and wood waste, energy crops, tallow seeds, switch grass, pine dust, aquatic plants, agricultural crops, and animal wastes (such as poultry litter and dairy manure) [26-27]. This technique involves a fuel feeding system and a reactor, in which the reactor makes the process more complex and expensive while comparing it with the pyrolysis process [11].

3.4.5 TECHNIQUE SELECTION

Though we have several techniques to process woody biomass, the deciding factor for selecting a technique is based on the form of energy we expect. In this work, we are interested in producing energy in the form of bio-oil from woody biomass and poultry litter. Based on our interest, pyrolysis and liquefaction are the better options to produce bio-oil. However, liquefaction process is dropped because of the complexity involved in its system. Hence, pyrolysis was rated as a better option to produce bio-oil.

3.5 PYROLYSIS

As discussed above, pyrolysis is a thermochemical process in which biomass is heated in the absence of oxygen [13-14, 28-29]. While heating biomass, it decomposes to produce different types of gaseous elements, and later these gaseous phase materials are passed through the heat exchanger to condense them in the form of liquid called bio-oil or pyrolytic oil [14]. However some fumes (non-condensable gases) are escaped out of the system because it is impossible to condense all the fumes produced by this process, and decomposed biomass are collected in the form of char. Thus, the three elements produced by this process are char (solid), bio-oil (liquid) and gases. Generally, bio-oil and char are the most attractive products obtained from this process and their production rate is entirely based on the operating parameters involved in this process [12]. Basically, there are three different types of pyrolysis process, and they are differentiated with respect to their operating parameters as shown below.

3.5.1 SLOW PYROLYSIS

This process is also called as conventional slow pyrolysis process and the term "slow" represents the heating rate of the biomass [12, 14]. Higher residence time (5 to 30 min) and the lower heating rates (approximately 5-7°C/min) are the basic operating conditions to achieve this process [12, 14]. Typically, primary product obtained through this process is char which leads to less liquid and gas production [12]. Certainly, as the temperature increases the production of char decreases and the yield of gas increases. At the same time, bio-oil yield increases with increase in temperature (about 550-600°C) and drops while operating above 600°C [12, 30].

3.5.2 FAST PYROLYSIS

Recently, people from different sectors have shown their interest towards this process because of its high bio-oil yield. Here, the biomass is heated rapidly to produce vapors and fumes and these gaseous products are quenched rapidly to obtain high yield of bio-oil (60-75 wt %) [14]. The typical operating conditions to achieve this process are high heating rates (usually 300°C/min) and lower residence time (0.5-2sec, <10sec is acceptable) [12, 14, 30-31]. Typically, high bio-oil yield was obtained between 450-550°C, however, char (15-25 wt %) and gases (10-20 wt %) are the other products acquired from this process. As the temperature increases the yield of char decreases and the yield of gas increases simultaneously [12, 14, 23, 30].

3.5.3 FLASH PYROLYSIS

This process is similar to fast pyrolysis process and the major difference in terms of operating condition is the residence time (approximately 30ms - 1.5 sec). Alike fast pyrolysis, bio-oil (50-75 wt %) is the primary product obtained from the flash pyrolysis, and char (5-25 wt %) [32] and gases (10-35%) are the other products of the process [12, 30-31]. Generally, for all the type of pyrolysis process, inert gas (nitrogen) is used to push the gases produced during the process, and it helps to achieve the required residence time easily. Apart from this, particle size (< 0.2mm for flash pyrolysis) of the biomass also plays a significant role in the pyrolysis process.

3.5.4 SELECTION OF PROCESS TYPE: FAST PYROLYSIS

As mention above, bio-oil is the primary form of bio-energy we are interested in and the Table-1 narrates the product yield (oil, char and gas) obtained from various pyrolysis processes.

Table 1: Products yield obtained from different pyrolysis processes [30].

Process	**Bio-oil, wt %**	**Char, wt %**	**Gas, wt %**
Slow pyrolysis	47	20	33
Fast pyrolysis	63	17	20
Flash pyrolysis	72	18	10

The data shown in Table 1 represent maximum yield of bio-oil produced from different types of pyrolysis process irrespective of the biomass type and temperature. It is evident that slow pyrolysis is not a better process to produce high quantity of bio-oil. However, fast pyrolysis and flash pyrolysis are the better options to produce high yield of bio-oil. In this work, fast pyrolysis is considered as the best option to produce bio-oil. The rationale behind selecting fast pyrolysis was, flash pyrolysis requires high energy input to grind biomass (biomass preparation), and it is still in the lab scale production stage. In addition, bio-oil produced from fast pyrolysis process is denser, and can be easily transported [30].

3.6 FEATURES INFLUENCING FAST PYROLYSIS PROCESS

Fast pyrolysis process can be carried out efficiently by high heating rates. However, this process requires few more essential features to produce better products and they are as follows:

3.6.1 DRY BIOMASS

Biomass obtained from the yards may have moisture content around 30-45 wt% and this wet biomass is not suitable for the process because it produces large quantity of water in the bio-oil [33]. Therefore, the biomass used for this process should be dried properly and the biomass can have less than 10 wt % of moisture content (up to 15wt % is acceptable) [14, 33]. The reason behind using low moisture content biomass was nothing but, during the process the moisture present in the biomass is transformed to water molecules and collected along with the bio-oil. These water molecules present in the bio-oil have negative effects on the stability, acidity, corrosiveness and other properties of the liquid [33].

3.6.2 PARTICLE SIZE

Particle size plays a significant role in the production of bio-oil during the process. Usually, biomass should be finely ground (0.6-1.25mm, up to 2 mm is acceptable) before processing it [12, 14, 29, 31]. However, particle size of the biomass is selected according to the type of the reactor (ablative reactors use whole tree chips) used for the process [29].

3.6.3 VAPOR RESIDENCE TIME

The time taken by the fumes or vapors to reach the heat exchanger (condenser) is called vapor residence time or shortly as residence time. Typically, quality fast pyrolysis process can be achieved while a residence time of 0.5 - 2 sec. (up to 5 sec is acceptable) [13-14, 29]. By processing at longer residence time, high temperature involved in the process will further crack the vapors and convert them into non-condensable liquids [29, 33]. Hence bio-oil yield will be reduced.

3.6.4 REACTION TEMPERATURE

Fast pyrolysis process requires controlled (absence of oxygen) pyrolysis reaction temperature of about 500°C [13-14, 29]. Typically the reaction temperature of about 425-500°C is used for this process [14, 23]. However, from woody biomass, maximum bio-oil yield (up to 80%) can be produced at 500-520°C with a residence time less than 1 second [13].

3.6.5 HEAT TRANSFER AND RAPID QUENCHING

Biomass is heated rapidly in fast pyrolysis process, and to achieve this, high heating rate is required. Basically, heat transfer can be achieved through three different modes of heat transfer such as conduction, convection and radiation. Table 2 describes the type of heat transfer involved in different types of reactor.

Table 2: Reactor types and heat transfer modes [13-14, 33].

Reactor type	Suggested mode of heat transfer	Bio-oil yield %
Ablative	95% Conduction; 4% Convection 1% Radiation	75
Circulating Fluid bed	80% Conduction; 19% Convection 1% Radiation	75
Fluid bed	90% Conduction; 9% Convection 1% Radiation	75
Vacuum	4% Conduction; 95% Convection 1% Radiation	35-50
Rotary cone	95% Conduction; 9%Conventional 1% Radiation	65
Auger	Direct contact with hot surface	30-50

Rapid quenching is the most essential feature which helps to produce high quality and quantity of bio-oil. Rapid cooling of pyrolysis vapors/aerosols results in producing bio-oil, and avoids the secondary reactions in the vapor phase [13-14, 29]. However, electrostatic precipitators are also used to recover aerosols [29, 33].

3.6.6 HEATING RATE

Yield of various products of pyrolysis are dependent on the heating rate followed in the process. It was observed that less bio-oil was produced at low heating rates (100°C/min), and it can be increased by increasing the heating rates to about 300°C/min. However, no significant change in the bio-oil production was observed while raising the heating rate over 300°C/min [29].

3.6.7 BIOMASS TYPE

Basically all kinds of biomass cannot produce same amount of bio-oil at fixed operating conditions because bio-oil production is based on the percentage of biomass constituents (cellulose, hemicellulose and lignin) [14].

3.7 REACTORS USED IN FAST PYROLYSIS PROCESS

Basically, fast pyrolysis process needs a reactor to carry out the process, and there are few types of reactors which named after the kind of structure and the mode of biomass feed followed to process the biomass. The list followed below mentions some of the commonly used reactors through which the fast pyrolysis process is carried out and they are as follows [12, 14, 34]:

- Bubbling fluidized-bed reactor
- Circulating fluidized-bed reactor
- Ablative reactor
- Rotary cone reactor
- Vacuum reactor

- Auger reactor

3.7.1 BUBBLING FLUIDIZED-BED REACTOR

Bubbling fluidized bed reactor is the most commonly used reactor for performing fast pyrolysis process, and it is commonly known as fluidized bed reactor. This reactor requires a carrier gas (nitrogen) for fluidization and to direct the gaseous elements (produced during the process) to the condenser [13]. It owns a good temperature control and can transfer heat effectively to the biomass particles. Usually sand is used as the solid phase of the bed in which the heat transfer takes place. Hence, sand selection plays an important role in processing the biomass. Further, this reactor is known for its high bio-oil yield production [14, 34]. Figure 5 shows a typical view of a bubbling fluidized-bed reactor.

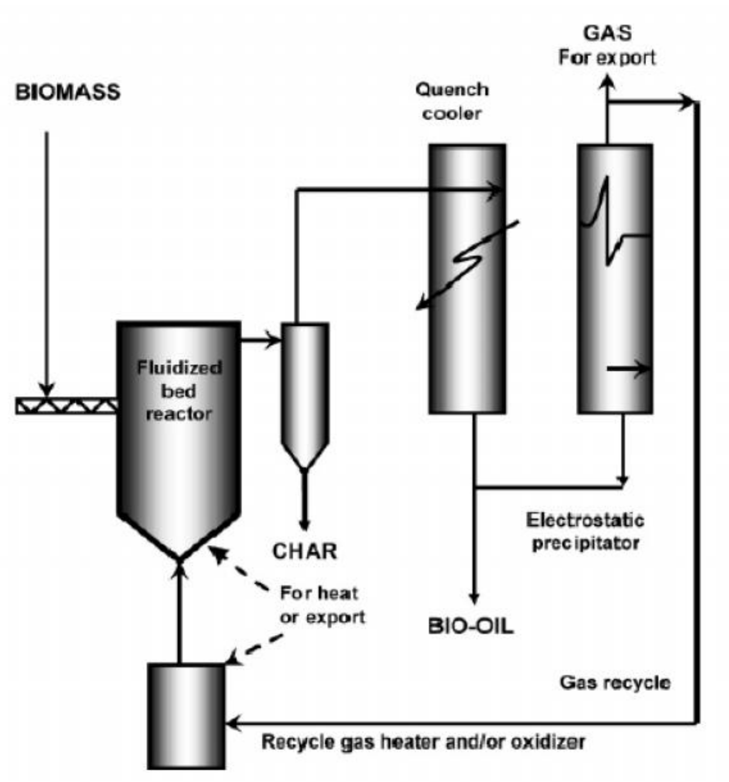

Figure 5: Process schematic of a bubbling fluidized-bed reactor [14].

3.7.2 CIRCULATING FLUIDIZED-BED REACTOR

Circulating fluidized-bed (CFB) reactor looks similar to the bubbling fluidized-bed reactor and the only difference in the design point of view is that it can re-circulate the sand particles involved in the process. In addition, it has a twin bed type in which the second vessel acts as a char combustor to reheat the circulating solids [14]. This makes the reactor design complex. Generally, convection mode of heat transfer is used to process the biomass, and Figure 6 shows a typical view of a circulating fluidized bed reactor.

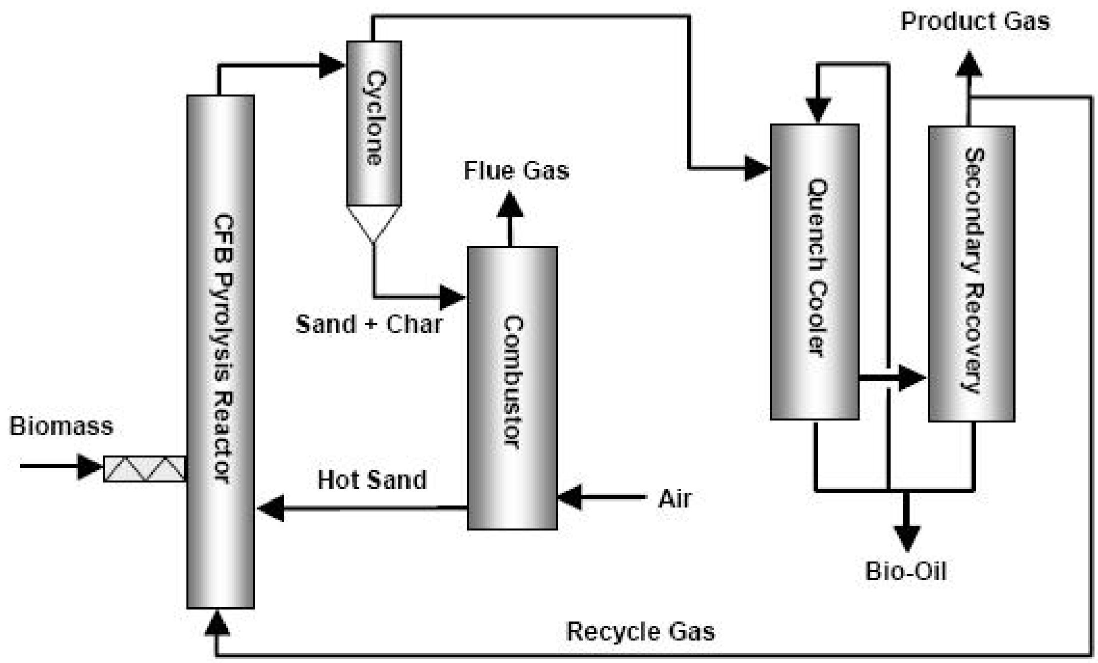

Figure 6: Process schematic of a circulating fluidized-bed reactor [34].

3.7.3 ABLATIVE REACTOR

It is a process where wood is pressed against a hot rotating surface and leaves an oil film behind which evaporates [13]. This process can accommodate large particles and does not require a carrier gas. Often, this reactor uses conventional vapor collection system such as quench column and electrostatic precipitator for collecting bio-oil [28]. However, this reactor is not popular because of its complex design.

3.7.4 ROTARY CONE REACTOR

In rotary cone reactor, pyrolysis reaction is achieved by the centrifugal force (force created while rotating the cone) which helps in mixing both hot sand and biomass and results in transporting the mixture. Basically, hot sand and biomass are fed into the base of the reactor, and as the cone rotates, the solid particles move upwards to the lip of the cone. The reaction progresses as the solid particles move upwards and fumes produced during the process are directed to a condenser. The char and sand are sent to the combustor where the sand gets reheated before sending it to the base of the cone (for recirculation). About 70% of bio-oil yield can be achieved by this process. However, complex design and scale up issues pulls down the popularity of the reactor [34].

3.7.5 VACUUM REACTOR

This reactor can achieve pyrolysis process at slow heating rates [13-14] which results in low bio-oil yield (30-45%) [34]. This process is highly complex because of the moving belt (which carries the biomass) and high temperature vacuum chamber. Apart from this, high maintenance and investment costs of the system make it more complicated for processing. However, it has several positive attributes such as clean oil production, use of larger feed particles (20-50mm) [34], and no carrier gas. The complexity of the system and low bio-oil yield did not encourage a lot of researchers to work on this reactor.

3.7.6 AUGER REACTOR

It is a compact system where the augers are used to move the biomass inside the cylindrical heated tube (reactor). In auger reactor, heat transfer can be achieved either by using hot sand or through coil/strip heaters mounted along the periphery of the cylindrical tube. The vapor residence time can be modified by changing the length of the hot zone and the use of carrier gas is optional. This reactor can produce bio-oil yield of about 65-75 wt% [14].

3.7.7 REACTOR SELECTION: AUGER

Although, we have several reactors to achieve fast pyrolysis process, auger reactor works better than other reactor types, Table 3 shows the comparison between different reactors involved in achieving the process.

Table 3: Comparison and relative merits of different reactors [35].

Property	Status	Bio-oil wt%	Comp-lexity	Feed size	Inert gas need	Specific size	Scale up
Fluid bed	Demo	75	Medium	Small	High	Medium	Easy
CFB	Pilot	75	High	Medium	High	Large	Easy
Entrained	None	65	High	Small	High	Large	Easy
Rotating cone	Pilot	65	High	V small	Low	Small	Hard
Ablative	Lab	75	High	Large	Low	Small	Hard
Auger	Lab	65	Low	Small	Low	Medium	Easy
Vacuum	Demo	60	High	Large	Low	Large	Hard
The darker the cell color, the less desirable the process.				Lab: 1 – 20 kg h^{-1} Pilot: 20 – 200 kg h^{-1} Demo: 200 – 2000 kg h^{-1}			

From the above table, dark colored cells refer the demerits involved in the reactors and as the number of dark cells increases (for a reactor type), the desirability of the reactor decreases. Certainly, auger reactor has less number of dark cells (needs small feed size particles) when compared to all the other reactors involved in this comparison study. Hence, it was selected for this study.

3.8 BIO-OIL

Bio-oil is the major product of the fast pyrolysis process and it usually looks like a dark brown mobile liquid with a distinctive smoky smell [28-29, 36]. This liquid fuel has numerous names such as pyrolysis oil, bio-oil, bio-crude-oil, bio-fuel-oil, wood liquids, wood oil, liquid smoke, wood distillates, pyroligneous tar, pyroligneous acid, and liquid wood [28].

3.8.1 PROPERTIES OF BIO-OIL

Bio-oil obtained from different biomass has different elemental and chemical compositions, and the properties of the bio-oil are basically dependent on the various factors such as feedstock type, production process, operating conditions and collecting efficiency [13]. Bio-oil is a multi-component mixture comprised of different size molecules derived primarily from de-polymerization and fragmentation reactions of three basic components of biomass such as cellulose, hemicellulose, and lignin [28, 37]. The chemical composition of bio-oil is highly complex as it was identified that bio-oil comprises of more than 300 compounds in which they can be classified broadly under the categories such as acids, alcohols, aldehydes, esters, ketones, sugars, phenols, guaiacols, syringols, furans, alkenes, aromatics and nitrogen compounds [34, 38]. Certainly, physical properties of bio-oil show some significant differences while comparing them with the properties of heavy/petroleum derived oil, and Table 4 shown below enumerates the same.

Table 4: Typical properties of wood pyrolysis bio-oil and of heavy fuel oil [37, 39].

Physical property	**Bio-oil**	**Heavy fuel oil**
Moisture content (wt %)	15–30	0.1
pH	2.5	-
Specific gravity	1.2	0.94
Elemental composition (wt %)		
C	54–58	85
H	5.5–7.0	11
O	35–40	1.0
N	0–0.2	0.3
Ash	0–0.2	0.1
HHV (MJ/kg)	16–19	40
Viscosity (at 50°C) (cP)	40–100	180
Solids (wt %)	0.2–1	1
Distillation residue (wt %)	up to 50	1

From the above table, the moisture content (water content) of the bio-oil is high when compared to heavy fuel oil and this is due to the moisture content present initially in the biomass. This high water content leads to high oxygen content of bio-oil (than heavy fuel oil) which apparently results in poor heating value (HV). Generally, at room temperature, viscosity of bio-oil (viscosity of bio-oil is different for different feedstock) is higher than the viscosity of heavy/petroleum derived oils. However, moderate preheating helps to reduce the viscosity of the bio-oil so that it can be pumped and transported easily. In addition, the low pH value of the bio-oil is due to the presence of organic acids, and this result in corroding common construction materials such as carbon steel and aluminum. However, they are noncorrosive to stainless steel [37, 39].

3.8.2 APPLICATIONS

Bio-oil from biomass is well known for its environmental and ecological merits, and these advantages help the oil to utilize it as an auxiliary fuel for petroleum based products. Apart from this, bio-oil and all the other products of the fast pyrolysis process have a wide range of applications and they are summarized in the Figure 7 as shown below.

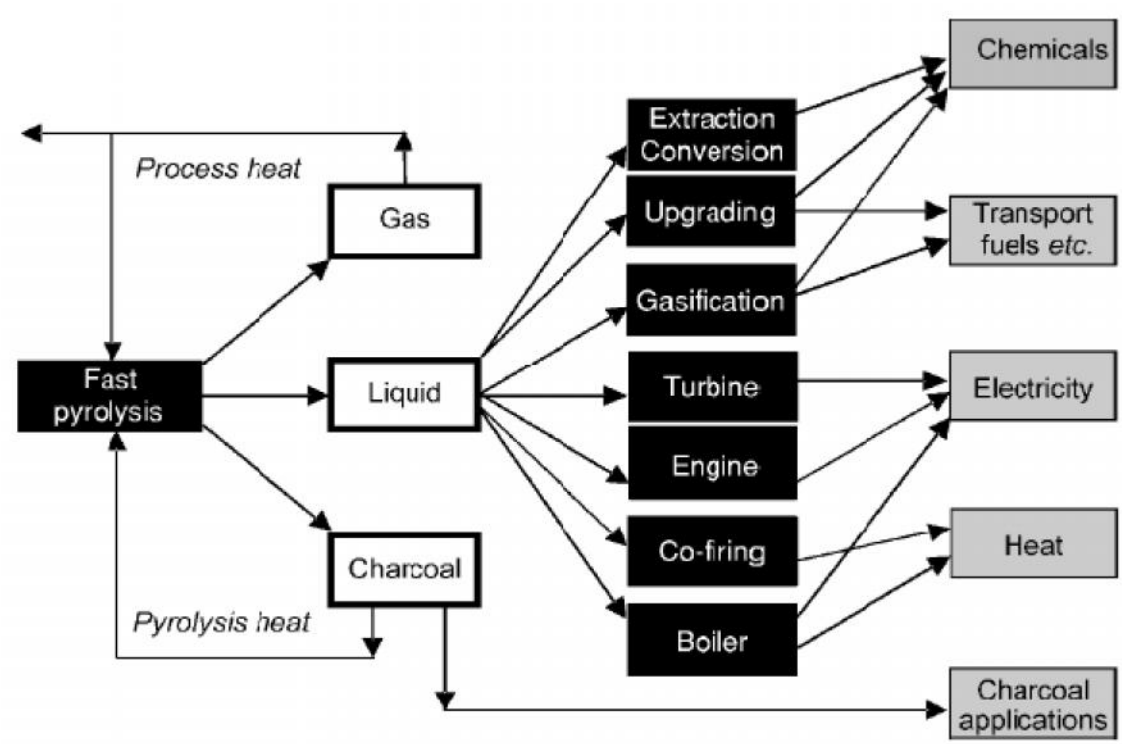

Figure 7: Fast pyrolysis and uses of its products [28].

Various products of fast pyrolysis process have numerous applications. However, bio-oil is our major concern and is being used in several areas (without upgrading) as described below.

A. COMBUSTION

Furnaces and boilers are the most commonly used systems for power generation, and they are less efficient than engines and turbines. Various studies were made to identify an alternative fuel for furnaces, burners and boilers, and it seems that bio-oil would be the suitable option for it as long as it has consistent characteristics, provides acceptable emissions level, and is economically feasible [28, 37, 40].

B. POWER GENERATION

Bio-oils are used in power generation by co-firing it with different fuels (diesel, heavy fuel oil and natural gas) in different equipment such as engines, gas turbines and stirling engines [37, 40-44]. Bio-oil has the potential to replace the conventional fuels in diesel engines (in low to moderate speed stationary diesel engines) and also in gas turbines by doing a minor modifications in the design of diesel engines and gas turbines [28, 34, 41, 45]. In addition, bio-oils can be emulsified with diesel for combustion in IC engines [46-47].

C. TRANSPORT FUEL

Bio-oils can be used as a transportation fuel by upgrading it. However, upgrading requires more energy and not economically efficient [28-29, 37].

D. CHEMICALS

Wood pyrolysis is major source of chemicals such as methanol, acetic acid, turpentine, tars, etc. This oil has more than 300 compounds and it is hard to separate those compounds using the current technology. Hence, by developing the current technology the compounds can be separated easily from the bio-oil [28, 37]. In addition, bio-oil is also used to produce special quality chemicals for pharmaceuticals and synthons, fertilizers, environmental chemicals and resins [29].

E. FOOD INDUSTRY

Currently, bio-oil is used in the food industry as food flavorings such as liquid smoke [29].

3.8.3 CHALLENGES

Though bio-oil obtained from fast pyrolysis process has numerous applications, the negative attributes possessed by it play a significant role in confining its utilization in the commercial market. Some of the major problems associated with bio-oil are described below:

A. HIGH OXYGEN CONTENT

Organic acids and water present in the bio-oil increases the oxygen content present in the bio-oil and thus decreasing the heating value of the fuel (less than 50% of that of conventional fuels) [37]. Bio-oil has 15-35% of water and by removing or reducing both water and other oxygenated compounds, oxygen content in the bio-oil can be decreased, and hence heating value can be improved [28].

B. HIGHLY ACIDIC

Typically, pH value of bio-oil obtained from woody biomass has low values (between 2 to 3). Hence, it is highly acidic. This results in corroding and damaging moving and non moving components of various equipment. Further, the severity of the corrosion increases with increase in temperature and water content [28]. Eventually, it (bio-oil) cannot be used in the existing refineries.

C. THERMAL INSTABILITY

Basically, thermal instability is due to the short residence time and rapid cooling of gaseous elements (produced during the process) from high temperature [48]. Apart from this, high oxygen content is also responsible for instability of bio-oil [37].

E. STORAGE PROBLEMS

Produced bio-oil en route for thermodynamic equilibrium, resulting in rise in viscosity and increase in molecular weight of the bio-oil [14, 28, 38].

F.CHAR AND ASH IN BIO-OIL

Fumes produced during this process are carried to the heat exchanger for cooling. As the fumes are condensed, the char and ash particles carried along with the fumes are collected in the bio-oil [14, 38]. Eventually, ash in bio-oil leads to corrosion and kicking problems in engines and valves [39].

3.9 ECONOMICS

Interest on fast pyrolysis process encourages to develop this technology and eventually implementing necessary steps to commercialize it. Certainly, several studies [34, 43, 49-51] were made to analyze the economic feasibility of the process, and it was found that feedstock cost, labor cost and operating variables are the most important variables in commercializing the technology. Figure 8 describes the various costs involved in operating the plant.

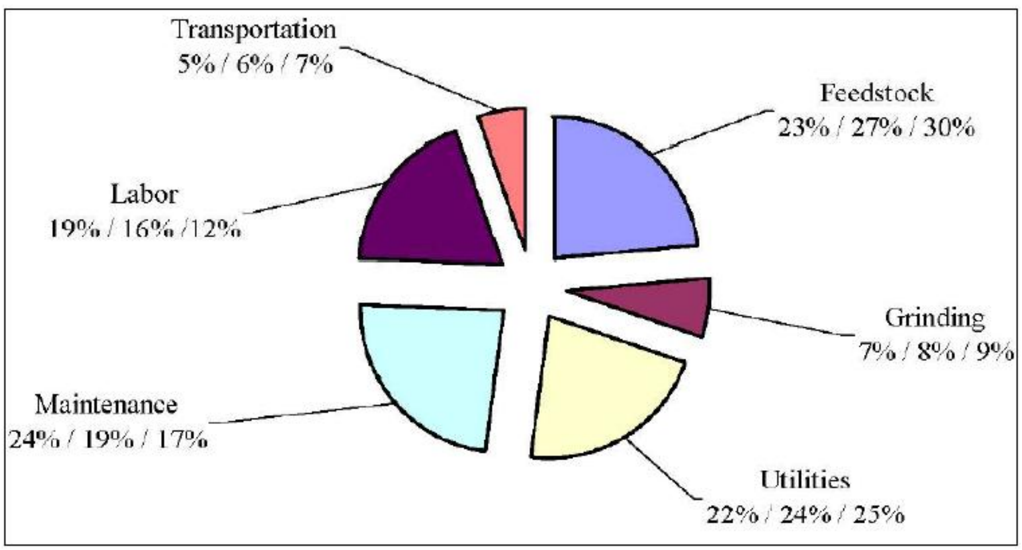

Figure 8: Operation Cost of 100/200/400 ton per day [49].

From the above figure, nearly half of the expenditure involved in operating the plant goes to feedstock and maintenance, and labor cost decreases while increasing the plant capacity, however, transportation, grinding and utilities cost increase with the increase in plant capacity. In addition, it was identified that the feedstock cost was different for different biomass such as

$30/ton, $20/ton, $42.50/ton and $20 for dry wood, peat, straw and rice husks respectively [34, 50, 52]. Table 5 shows the bio-oil production cost with respect to plant size and total capital investment.

Table 5: Bio-oil production cost [34].

Plant Size (ton/day)	**Feed Cost ($/ dry ton)**	**Bio-oil Cost ($/kg)**	**Bio-oil Cost ($/gal)**	**Total Capital Investment ($)**
2.4	22	0.38	1.73	97,000
24	22	0.18	0.82	389,000
100	36	0.26	1.21	6.6 million
400	36	0.19	0.89	14 million
1000	44	0.11	0.50	46 million
1000	20-42.5	0.13-0.54	0.59-2.46	44-143 million

Table 5 clearly elaborates the bio-oil production cost and total capital investment involved in different fast pyrolysis plant. Here, we can notice that as the capacity of the plant increases, the cost involved for constructing the plant (total capital investment) increases and the production cost on bio-oil decreases. Certainly, the cost on feedstock plays a significant role in bio-oil cost.

CHAPTER 4

EQUIPMENT AND MEASURING DEVICES

This chapter comprises the materials, equipment and measuring devices involved in various stages of this research (production and analysis of bio-oil). It also includes the various features (sub-components of major equipment) and the technical specification of the various equipments used in the experimental setup. In addition, measuring devices, furnace and conventional oven used in measuring the physical properties of the products (biomass, bio-oil and char) and the methods involved in measuring those physical properties were incorporated in this section.

4.1 AUGER REACTOR

The machine shown below in the Figure 9 is an auger reactor. Basically, the construction of this reactor have various subassemblies such as hopper (with nitrogen port), reactor (reactor pipes, auger, heaters and insulation), power transmission system (motor and battery), heat exchangers, char collector, cooling system (chiller), and exhaust system.

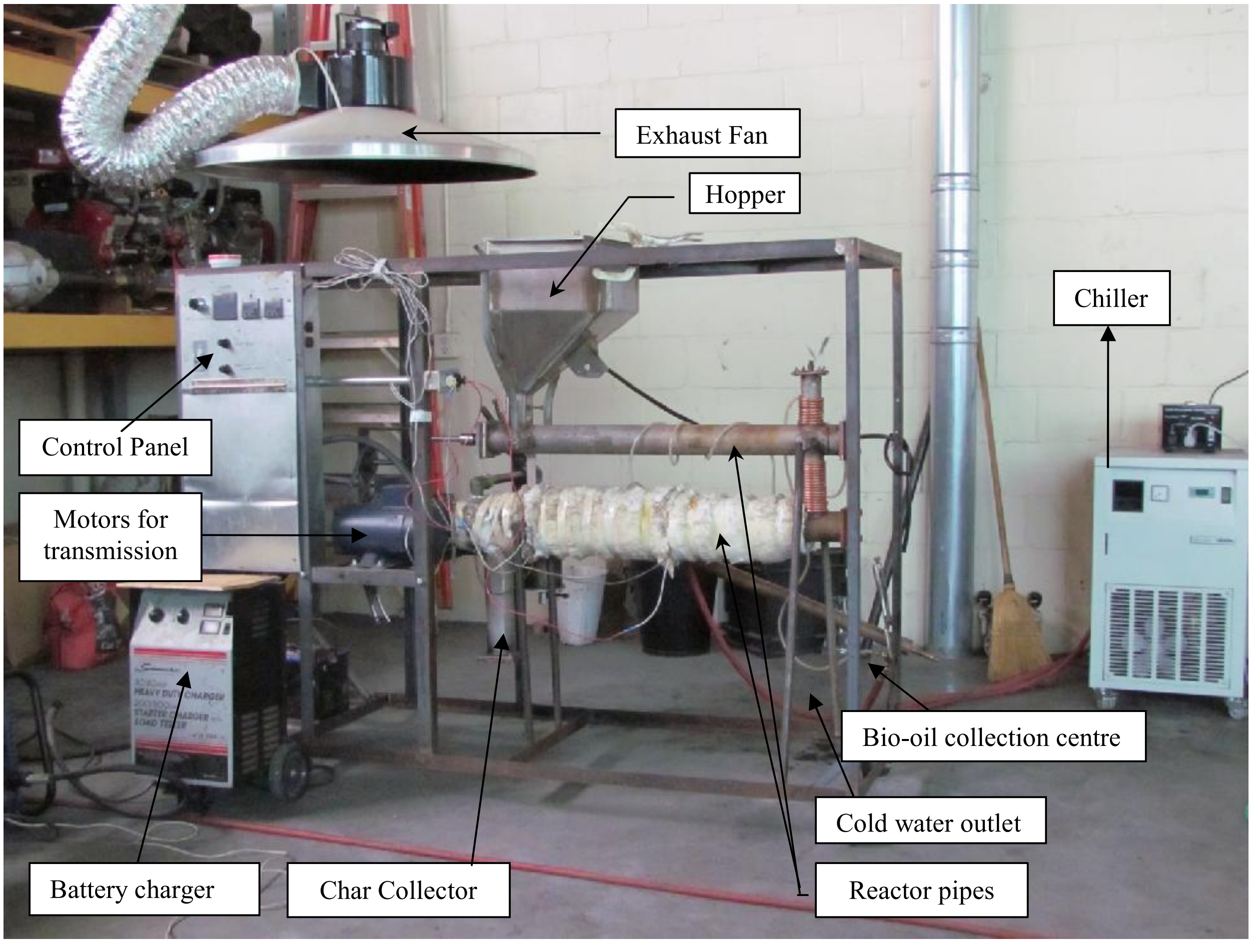

Figure 9: Auger reactor at Auburn University

The functions and the technical specification of various subassemblies involved in designing the reactor were given below:

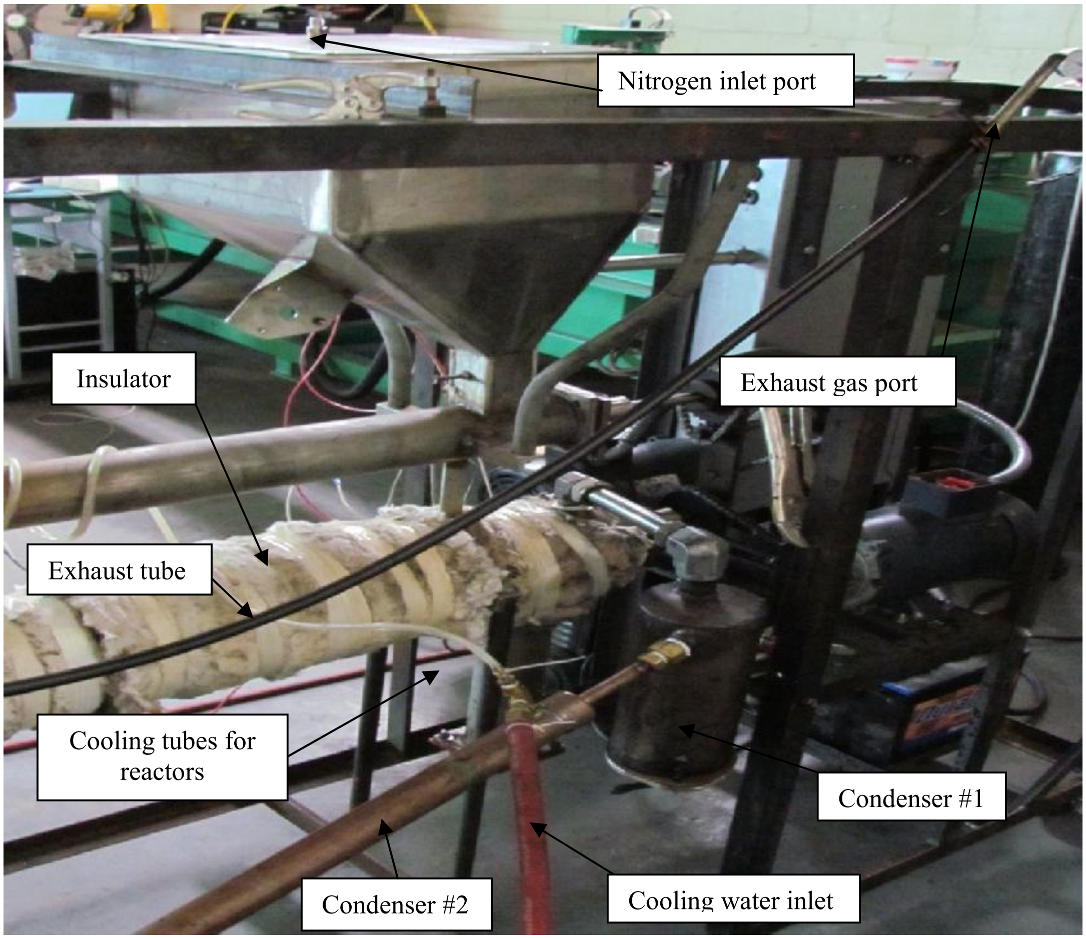

Figure 10: View on heat exchangers and exhaust gas port.

4.2 HOPPER

Hopper was used to store the biomass temporarily, and the biomass can be extorted (as per the requirement) into the reactor using the augers mounted below the hopper. While processing biomass, hopper should be closed all the time (to maintain oxygen free atmosphere). In addition, a vent was provided at the top of the hopper for purging nitrogen into the system as shown in the Figure 10. Technical specifications of the hopper were listed below:

Material: Aluminum

Maximum capacity: 1.2 kg

4.3 REACTOR

Reactor is the heart of the system where the actual process (fast pyrolysis) takes place and it consists of reactors pipes, auger, heaters and insulation.

4.4 REACTOR PIPES

There were two cylindrical pipes mounted below the hopper (one below the other) in which one such cylinder was attached to the bottom end of the hopper to receive and supply the biomass towards the hot zone (stored in the hopper). Technical specifications of the reactor pipes were listed below:

Top reactor pipe:

Material: Stainless steel

Length: 1000 mm

Effective length: 800 mm (distance travelled by the biomass in the pipe)

Outside diameter: 76.2 mm

Inside diameter: 71.4 mm

Bottom reactor pipe:

Material: Stainless steel

Length: 1092.2 mm

Effective length: 863.6 mm

Outside diameter: 76.2 mm

Inside diameter: 71.4 mm

4.5 AUGER

It is also called as screw feeder. Here, it was mounted inside the reactor pipes and supported by the bearing provided at both the ends of the reactor pipes. The openings of the reactor pipes were sealed by a stainless steel plate, however, one end of the plate (on each reactor tube) was provided with an opening for mounting the transmission system to drive the augers inside the reactor pipes. The technical specifications of the augers were listed below:

Top auger:

Material: Stainless steel

Length: 1000 mm

Nominal diameter: 69.85 mm

Pitch: 76.2 mm

Route diameter: 15.875 mm

Flight thickness: 4.77 mm

Direction: Right hand

Speed: 6 rpm (app.)

Bottom auger:

Material: Stainless steel

Length: 1092.2 mm

Nominal diameter: 69.85 mm

Pitch: 76.2 mm

Route diameter: 15.875 mm

Flight thickness: 4.77 mm

Direction: Right hand

Speed: 25 rpm (app.)

4.6 HEATERS

Three heaters were mounted along the periphery of the bottom reactor pipe to supply heat to the reactor. Typically, strip heaters were used for this purpose, and they were mounted in the form of coils along the cylindrical surface (of the reactor pipe). The technical specifications of the heaters were listed below:

Type: Strip heaters or flexible heating tapes

Quantity: Three (3)

Part no: STH101-040

Volts: 120

Watts: 627

Size: 25.4 x 1219.2 mm

Amps: 5.23

Heating length: 508mm

4.7 INSULATION

Insulators were mounted above the heaters and also along the bottom reactor pipe to avoid the heat loss while operating the heaters. Basically ceramic fiber blankets were used for this purpose and they can resist as high as 2025°C.

4.8 POWER TRANSMISSION SYSTEM

This system (includes a pair of DC motors, battery and battery charger) provides power required to rotate the augers installed inside the reactor pipes and the DC motors were couples with the augers using sprocket and chain assembly. Basically, battery was charged by the battery charger, and hence supplying the necessary power to the motors. Technical specifications of the motor were listed below:

Type: DC motors

Quantity: Two (2)

Power: 0.75 HP

Volts: 24

Amps: 29

Speed: 1800 rpm

Torque: 26.3

4.9 CHAR COLLECTOR

It is a small cylindrical tube (welded perpendicular to the bottom reactor tube) used to collect the biochar produced from the fast pyrolysis process. Here, one end of the collector was attached to the reactor side, whereas the other end of the reactor is closed using a stainless steel plate (to maintain oxygen free atmosphere). Dimensions and capacity of the char collector were listed below:

Material: Stainless Steel

Length: 330.2 mm

Outer diameter: 76.2 mm

Inside diameter: 71.4 mm

Maximum capacity: 400 g

4.10 HEAT EXCHANGERS

Condensers are the basic heat exchanging units installed to this system (to condense the fumes produced by the reaction). Here, two different condensers with different geometric shapes were used to collect the bio-oil, in which one condenser (condenser #1) was fixed near the bottom reactor, and the other (condenser #2) was mounted after its predecessor. The rationale behind the geometry (cylindrical) of the heat exchangers was nothing but easy maintenance. The dimension and material of the heat exchangers were listed below:

Condenser #1:

Length: 254 mm

Diameter: 114.3 mm

Thickness: 2mm

Cooling area: 112000 mm^2

Temperature: Atmospheric temperature

Cooling medium: Air

Condenser #2:

Length: 1092.2 mm

Outer diameter: 47.625 mm

Inner diameter: 15.875 mm

Material: Copper

Cooling length: 838.2 mm

Cooling area: 42200 mm^2

Temperature: -1 °C

Cooling medium: Water and ethyl glycol

4.11 COOLING SYSTEM

The cooling system includes chiller and supporting cooling tubes for the reactor. The function of the chiller was to produce (to reduce the temperature of the coolant) and supply the coolant to the condenser #2 and to the cooling tubes. The function of the cooling tubes (coiled along the connecting pipe of the top and bottom reactor pipe) was to reduce and restrict the heat produced by the heaters to reach the top reactor pipes. Technical specification of the chiller was listed below:

Make: LAUDA DR.R. WOBSERGMBH & CO. KG

Model: LAUDA WK class WKL 1200 W

Maximum filling capacity: 23 litters

Maximum flow: 40L/min

Temperature: -1 °C

Accuracy: ± 0.5 °C

Coolant: water and ethyl glycol (3:1 ratio respectively)

Cooling tube material: Copper

4.12 EXHAUST SYSTEM

This system comprises of exhaust tube and exhaust fan (as shown in the Figures 9 and 10) in which, one end of the exhaust tube was attached to the outlet of the condenser #2, and the other end was vented out to exhaust fan (to suck the non condensable gases produced during the process).

4.13 INSTRUMENTS USED FOR DETERMINING VARIOUS PHYSICAL PROPERTIES

This session includes various measuring devices, furnace and conventional ovens used to quantify different physical properties of bio-oil.

4.13.1 MEASURING BALANCE

It was used to quantify the weight of bio-oil, filter paper, char and crucibles. This instrument was used in determining almost all the physical properties of bio-oil (except acidity and kinematic viscosity) and char involved in the work. Figure 11 shows the balance used for this project and its technical specifications were listed below:

Figure 11: Measuring balance

Name: Mettler Toledo

Model: AB 204-S/ FACT

Maximum measurable weight: 220 g

Minimum measurable weight: 0.1 mg

Accuracy: ± 0.2 mg

4.13.2 pH METER

It is an electronic instrument used to determine the acidity of a liquid. The instrument being used in our laboratory (as shown in the Figure 12) was manufactured by OAKTON instruments (Model: PH510 Series) and the accuracy of the instrument is about ± 0.1.

Figure 12: pH meter

Figure 13: Pycnometer

4.13.3 DENSITY BOTTLES

Density bottles are technically known as pycnometer/Gay-Lussac bottles, and they are used to determine the specific gravity of the liquid. Figure 13 shows a typical pycnometer used in our laboratory and its technical specifications were listed below:

Dimensions: 32 mm H x 17 mm OD

Capacity: 2 mL

Brand: PYREX

Model: 1622-2

4.13.4 FILTER PAPER

Filter paper was used to determine the solid content of the bio-oil, and papers used in this work were manufactured by Whatman limited. The specifications of the filter paper were listed below:

Grade: Grade1 (11µm)

Diameter: 70mm

Cat No: 1001070

4.13.5 MECHANICAL CONVENTIONAL OVEN

This oven (as shown in the Figure 14) was used while determining various physical properties such as solid content (bio-oil) and moisture content of biomass and bio-char. This instrument was manufactured by precision instruments (Model: STM 80), and they were generally operated at 105°C to remove moisture content of the filter paper and bio-based materials. Accuracy of this conventional oven was about ± 2 °C.

Figure 14: Mechanical conventional oven

4.13.6 FURNACE

Basically, in this work, furnace was used to determine the ash content of the bio-based materials (bio-oil, char and biomass). Figure 15 shown below was the typical thermolyne atmosphere controlled ashing furnaces used in our laboratory, and it was manufactured by Thermo Scientific. The technical specifications of the furnace were given below:

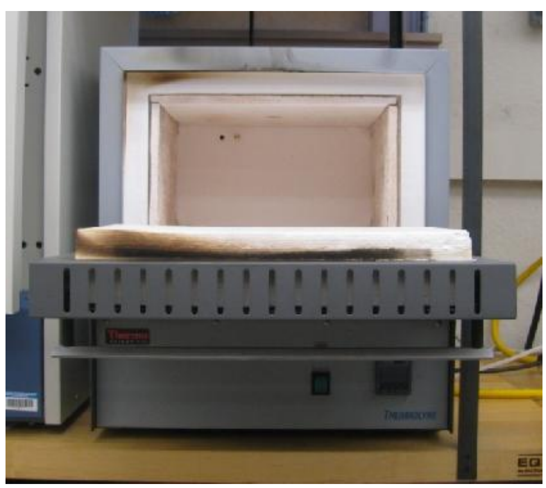

Figure 15: Thermolyne atmosphere controlled ashing furnace

Type: F6000

Max. Temperature: 975 °C

Max. Temperature gradient: ±3 °C at 750 °C

Capacity: Can accommodate 24 (30mL) porcelain crucibles or 38 (10mL) quartz crucibles

Heating rate: 8 °C/min. to 500 °C, 6 °C/min. from 500 °C to 750 °C

4.13.7 BOMB CALORIMETER

This instrument was used to determine calorific value (heating value) of bio-based materials used in this work and the instrument used in our laboratory (as shown in Figure 16) was manufactured by IKA groups. Technical details of this calorimeter were given below:

Model: IKA C200 calorimeter

Part No: 8802501 C 200

Dimensions: 400 x 400x 400 mm

Measuring time: 14 min

Figure 16: C200 Bomb calorimeter

Figure 17: CVO Rheometer

4.13.8 RHEOMETER

Rheometer was used to determine the kinematic viscosity of the liquids (bio-oil) and the instrument used in our laboratory (as shown in Figure 17) was manufactured by Bohlin Instruments (Model: CVO Rheometer). It has various features such as integrated microprocessor controlled electronics, automatic gap zeroing and adjustment, unique air bearing technology, wide torque range, micro strain position sensing, high speed capability and controlled shear rate mode.

4.13.9 AQUAMETRY APPARATUS

This apparatus was used to determine the water content present in the bio-oil, and the schematic view of the apparatus was shown in Figure 18. Apart from the various parts shown in the Figure 18, methanol (solvent) was another important element used while measuring the water content of the bio-oil sample and the specifications of this apparatus were given below:

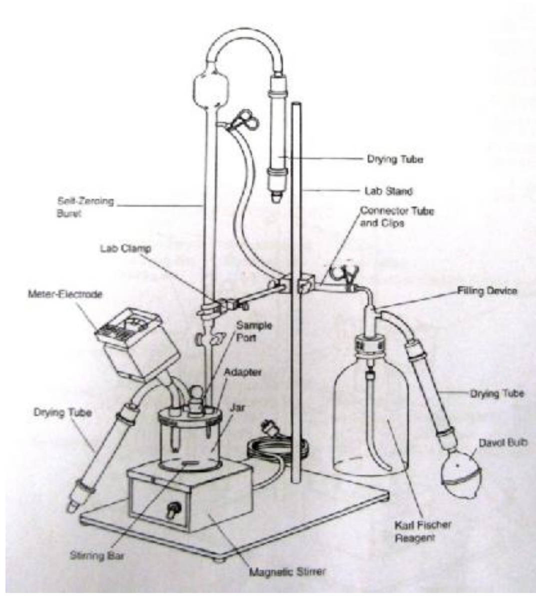

Figure 18: Aquametry apparatus

Accuracy: 1% of full scale volume

Reproducibility: 0.5% of full scale volume

Moisture determination: Ranges from 5ppm to 100% water

Operating conditions:

Temperature: 17 °C to 27 °C

Relative humidity: 20% to 80%.

CHAPTER 5

MATERIALS AND METHODS

This chapter details the materials (different biomass) and methods implemented along the various stages of this project. Three different biomass types were investigated in this study and in general, raw biomass has to be preprocessed before they can be fast pyrolyzed. Here, various methods involved in processing and characterizing biomass and in bio-oil production were discussed below. In addition, methods involved in analyzing different physical properties of bio-oil and biochar were also detailed here.

5.1 BIOMASS PREPARATION AND CHARACTERIZATION

As mentioned above, three biomass types such as pinewood, underutilized forest biomass and poultry litter were obtained from different resources. Pine wood chips were obtained from a local wood chipping plant in Opelika (AL); underutilized forest biomass was collected from the USDA- Forest Service at Auburn (AL); and poultry litter was acquired from a poultry house of Auburn (AL). During the collection of different biomass, it was observed that pine wood obtained from the wood chipping plant was pure (only wood chips and no adulteration of barks and leaves) as shown in Figure 19, whereas the underutilized forest biomass consists of woodchips, barks, twigs, dry leaves and other residues acquired from forest thinning operation (as shown in Figure 20). Poultry litter was the combination of litter and bedding material used in the poultry house (as shown in Figure 21).

Figure19: Pictorial representation of pinewood biomass

Figure 20: Pictorial representation of underutilized forest biomass

Figure 21: Pictorial representation of poultry litter biomass

Actually, both pinewood and underutilized forest biomass were broadly classified under woody biomass; whereas poultry litter comes under animal manure category. In this work, woody biomass were made to pass through the entire preprocessing stage (drying, grinding and sieving) however, poultry litter has gone through sieving stage only (as drying and grinding steps were not required). Certainly, woody biomass were dried in a conventional oven for 24 hr at 75°C and ground using a hammer mill (New Holland Grinder Model 358) fitted with 3.175mm (1/8 inch) screen size. Later, both the woody biomass (ground) and poultry litter were fractionated through a simple sieve analysis and the particles in the range of 0.841 to 1.41mm (US Sieve No. 14-20) were used in this study. While fractionating the biomass, sieves used in the process were cleaned properly before and after changing the biomass type (to avoid biomass mixing).

Bulk density of different biomass samples were calculated by filling a known amount of biomass in a given volume of measuring cylinder (100 mL). Moisture and ash contents of the biomass (wet basis) were determined according to the standards ASTM E 871 and ASTM E 1755, respectively. An oxygen bomb calorimeter (IKA, model C200) was used to measure the higher heating value (HHV) of biomass. Table 6 (refer Appendix A.1-A.3) shown below records the biomass sample characterization of different feedstocks involved in this study.

Table 6: Biomass sample characterization

Properties	**Pinewood**	**Underutilized forest biomass**	**Poultry litter**
Bulk density, g/cc	0.32	0.26	0.52
Moisture content , wt.%	7.51	4.98	12.76
Particle size, mm	0.84 - 1.4	0.84 - 1.4	0.84 - 1.4
Ultimate analysis, wt.%			
C	46.26	47.86	27.11
H	5.62	5.81	4.32
O*	47.66	45.36	31.35
N	0.13	0.08	3.1
S	◊	◊	0.61
Ash, wt.%	0.31	0.89	34.68
Higher heating value, MJ/kg	18.66	18.07	9.66

“*”calculated by the difference (100 minus the weight of carbon, hydrogen, nitrogen, sulfur and ash); “◊”below detection limit.

From Table 6, the sample characterization of both pinewood and underutilized forest biomass looks alike, however the ash content of underutilized forest biomass was approximately three times higher than pinewood and this was due to the residues present in the biomass. Certainly, poultry litter has higher ash and moisture content when compared to woody biomass. However, heating value of poultry litter was much lower than the woody biomass.

5.2 BIO-OIL PRODUCTION USING AN AUGER REACTOR

In this project, an auger reactor (designed and fabricated at Auburn University) was used to produce bio-oil from different biomass through fast pyrolysis process. This section describes the basic working procedure followed in operating the reactor to produce bio-oil from biomass. Figure 22 represents the basic material flow process involved of an auger reactor. Generally, the reactor was operated at four different temperatures (for the first objective alone) to investigate the effect of temperature on bio-oil yield and its physical properties. Two condensers were installed to collect the bio-oil in which the first condenser was operated at room temperature; whereas, the second condenser was maintained at 0 °C to condense vapors and aerosols escaped from the first condenser.

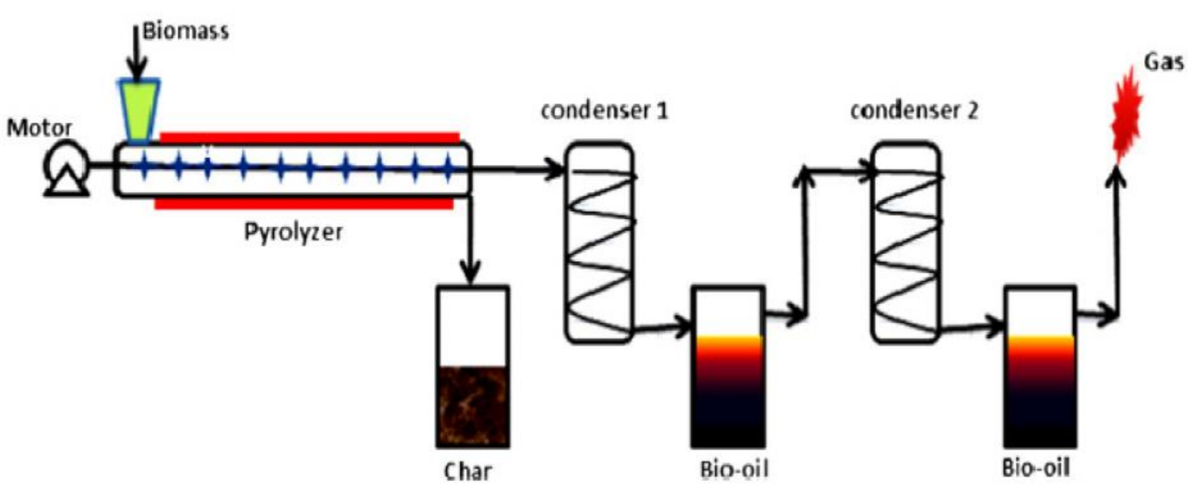

Figure 22: Typical material flow process of an auger reactor

Certainly, for each experiment, a known amount of biomass (500 g) was fed into the auger reactor to produce bio-oil and the reactor was maintained at inert atmosphere by purging nitrogen gas before the pyrolysis process. As the biomass advances to the hot zone of the auger reactor/pyrolyzer, it gets decomposed and produces gases, vapors and aerosols. These gaseous elements were then condensed as liquid (bio-oil) using the two condensers and the bio-oil obtained from those condensers were mixed together to measure the total yield of bio-oil whereas the decomposed biomass (char) are dumped into the char collector. Bio-oil and bio-char yields were calculated by measuring their weights at the end of each experiment; whereas, the gas yield was determined from the difference (100 minus the sum of the weight of bio-oil and bio-char).

5.3 BIO-OIL ANALYSIS

Bio-oil obtained from different biomass through the auger reactor (at different temperatures) was further analyzed to determine its physical properties such as pH, density, viscosity, water content, solid, ash and higher heating value.

The pH value of bio-oil was measured using a digital pH meter (Oakton, Model PC 510) and the density of bio-oil was measured using a calibrated 2 mL density bottle (Cole-Parmer Model EW-34580-40). Viscosity measurements were conducted using a rheometer (Bohlin Model CVO 100) at 40°C and dynamic viscosity (Pa.s) data were obtained as a function of shear rate (0.1 - 100s^{-1}). Water content of bio-oil samples was calculated by Karl-Fischer (KF) analysis using a Barnstead aquametry II apparatus (Cole-Parmer Model EW-25800-10). In the volumetric KF titration, the water equivalence of KF reagent (mg of H_2O/mL of KF reagent) was calculated and the water content of bio-oil was measured by dissolving a known amount of sample in methanol and titrated against the KF reagent (purchased from Sigma Aldrich).

The solid content in the bio-oil was measured by mixing one gram of bio-oil with 100 mL of ethanol in a beaker and the solution was filtered through a dried and pre-weighed Grade 1 (11 μm pore size) filter paper. This filter paper was dried in an oven at 105 ^{o}C for 30 min and the insoluble materials remained on the dried filter paper was weighed for solid content. The ash content and the heating value of bio-oil were determined alike biomass. Each measurement was carried out in triplicate and their average values were reported in this study.

5.4 BIOCHAR ANALYSIS

Another major product of the fast pyrolysis process is biochar and its physical properties such as moisture content, ash content and heating value were also analyzed. The measuring procedure for determining these physical properties were described in the section 5.1.

CHAPTER 6

STATISTICAL DESIGN OF THE EXPERIMENTS

This chapter presents the design of experiments and the statistical analysis followed in this project. In addition, it also includes the working procedure (cleaning and inspection) followed along the course of the work.

6.1 FACTORS AFFECTING THE PROCESS

Basically, the design of experiments was modeled according to the measurable or controllable factors affecting the process (though we have other factors affecting the process as mention in the section 3.7). Figure 23 shown below illustrates all controllable and uncontrollable factors affecting the reaction and all the measurable parameters of the bio-oil.

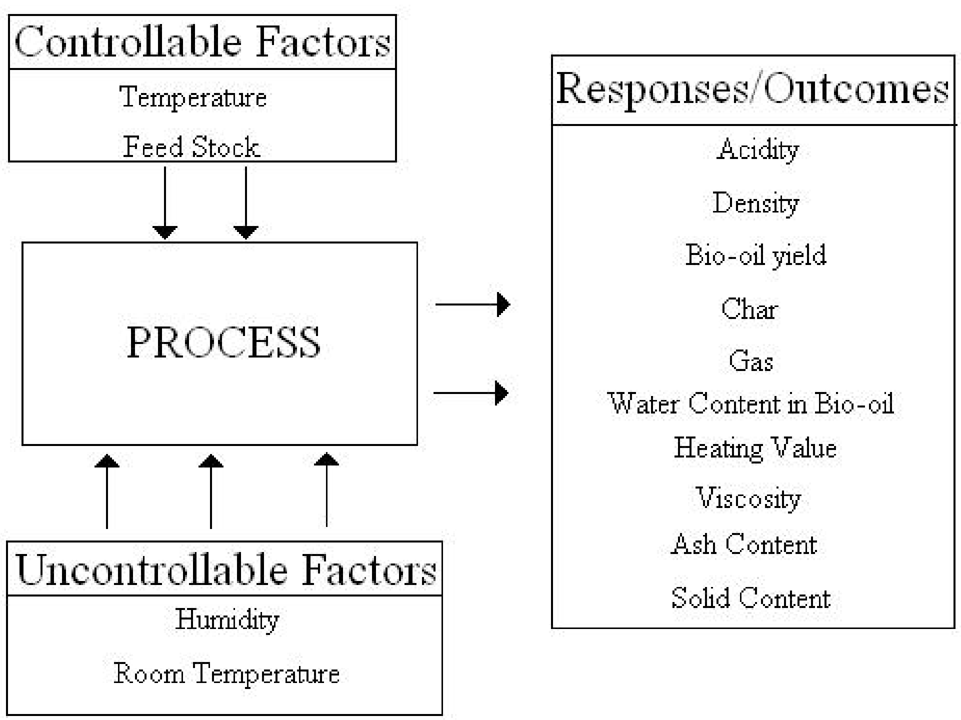

Figure 23: Various factors affecting the process

From Figure 23, temperature and feedstock were the two controllable factors of the reaction and in this work, there are four levels of temperatures and three levels (type of biomass) of feedstocks were involved. However, three iterations (for each combination of the factor levels) were planned to carry out statistical analysis of the results and hence 36 iterations were scheduled for the first specific objective.

As the objective of this work was to increase the pH value of the bio-oil through simple and economic methods, for the second specific objective (production of bio-oil using sacrificial bio-based additive), feedstock was the major controllable factor (as the operating temperature and primary feedstock were determined from the previous objective). Here, three levels (weight percentage of the additive) of feedstock were considered and three iterations were planned for this study. As a whole, three different feedstocks at one operating temperature with three iterations were scheduled to 9 experiments.

For the third specific objective (production of bio-oil using cascade pyrolysis reactors), two different levels of operating temperatures and one type of feedstock (determined from the first objective) with three iterations were planned, eventually, 6 experiments were scheduled for the third objective. All the experiments (51 iterations) were planned and completed in two months and the analysis part (determining various physical properties of bio-oil and char) took another month.

6.2 WORKING PROCEDURE

The following were the list of activities (cleaning and inspection) followed for every experiment involved in this work.

List of cleaning activities to be carried out before starting every experiment:

- Biomass hopper should be cleaned properly using a cloth and compressed air.

- Cleaning interiors of stainless steel tubes (top, bottom reactors) and augers (screw conveyors) using wire scrubber and wire brush respectively whenever changing of biomass is required.
- Condensers should be cleaned thoroughly using acetone/methanol, water and compressed air whenever changing of biomass is required.
- Bio-char collector shall be cleaned using a wire scrubber and compressed air.

List of equipment to be inspected before starting every experiment:

- Visual inspection on biomass hopper and bio-char dumper are required.
- Inspection on reactors and condensers are carried out visually using compressed air.
- Reactors and bio-gas line are checked for leaks by purging nitrogen gas at 10 psi pressure and making sure that no leaks persists before starting the experiment.

CHAPTER 7

EXPERIMENTAL RESULTS

This chapter comprises of all the experiments involved in this work and it also includes a brief background, results and discussions on the experiments involved in each objective of this project. In addition, it also contains a short remarks section which narrates all the key observations and decisions taken while executing various stages of the project. Basically, this section is further subdivided into three parts (as per objectives) in order to elaborate the experiences gained while performing various objectives (experiments) involved in this project.

7.1 PRODUCTION OF BIO-OIL FROM SELECTED BIOMASS

In this work, producing bio-oil from selected feedstocks was considered as the first step to meet our prime objective (producing bio-oil with high pH value) of our project. Here, general information about the process, biomass used, ideas followed and their consequences were detailed below.

7.1.1 SUMMARY

From Chapter 3, we know that fast pyrolysis is a thermochemical process (biomass to liquid conversion process) which has attracted a lot of interest from industry and academia due to its high oil yield (the expected form of bio-energy, in this work). Bio-oil can be produced from different biomass feedstocks that are regionally appropriate. In this work, bio-oil was produced from pine wood, underutilized forest biomass and poultry litter at selected temperatures in between 425-500^{o}C using an auger reactor. Physical properties of bio-oil, such as pH, density, higher heating value, ash, water and solid content were analyzed and compared with an ASTM standard to document the effect of pyrolysis temperature. From the analysis, all the properties of the bio-oil obtained from woody biomass met the specifications suggested by the ASTM standard (except for ash content). However, density, water content and higher heating value of bio-oil obtained from poultry litter did not meet the ASTM standard. In addition to aforementioned analyses, kinematic viscosity of bio-oil was also measured and it showed that at higher shear rate, bio-oil behaved as a Newtonian fluid (constant viscosity). Furthermore, physical properties of biochar were measured and analyzed.

7.1.2 INTRODUCTION

As mentioned above, environmental concerns, national energy security and climate change are the primary reasons to explore alternative energy resources. Significant amount of resources has been devoted in producing transportation fuels from biomass and other resources. Liquid fuels are the most attractive alternative due to its competitive cost structure. The most common method for converting biomass to liquid fuels is generally achieved by thermochemical and biochemical processes. Here, fast pyrolysis was opted to produce liquid fuel (bio-oil) and auger reactor was selected to achieve this process, and the rationale behind these selections was already detailed in Sections 3.5.4 and 3.8.7, respectively.

The products of the fast pyrolysis process are bio-oil, bio-char (solid left after pyrolysis) and gases, in which bio-oil is the major product, and it is in the form of liquid that can be easily stored and transported. Further, it reduces the issues related to biomass logistics. This process is well known for its flexibility in accepting different types of biomass. Basically, biomass such as bagasse, pinewood, hazel nut shell, pine sawdust, switch grass and mixed wood waste are used in this process; however, pinewood (pure form of pinewood chips), underutilized forestry biomass (forest residues) and poultry litter (animal waste) were selected for this project and the reasons behind selecting these feedstocks were given below.

Based on the Billion-Ton study, the U.S. has a capacity to produce about 368 million dry tons of forest residues annually, and another study conducted by Milbrandt (2005) showed that wood residues account for 39% of total biomass available in the U.S. [5, 53]. Further, Alabama State has a potential to produce 2.81 million dry tons of forest residues, 64 million dry tons/year of logging and other residues, 6.45 million dry tons of primary mill residues, 63 thousand dry tons of secondary mill residues, and 532 thousand dry tons of urban wood residues annually. As the availability of the woody biomass is huge in the southern parts of US, especially in Alabama, pine wood and underutilized forest biomass were selected.

Here, poultry litter was also selected as a feedstock (in this work) because of its availability in United States of America. US is the largest producer of poultry litter in the world, and it produces nearly 11 million tons of poultry litter (broiler litter) in 2008 [54]. Further, Alabama State ranks third in poultry litter production (after Georgia and Arizona) and it produces 1.2-1.3 million tons of broiler litter during 2008-2009 [54] and Alabama Co-operative Extension System states that Alabama have produces 1.2 to over 1.8 million tons of poultry litter annually, and is expected to reach 2 million tons by 2011. Basically, poultry litter is used as a fertilizer in Alabama.

In this objective, the selected biomass were fast pyrolysed to produce bio-oil and the various properties of the liquid (obtained from the process) were further analyzed to comprehend the behavior of the biomass and their properties of respective bio-oil at different operating temperatures. Methods involved in producing and analysis bio-oil and biochar are already elaborated in the Chapter 5.

7.1.3 RESULTS AND DISCUSSIONS

In this section, the results obtained from processing different biomass at different operating temperatures (such as yields of bio-oil, char and gases) were reported. In addition, analysis on different physical properties of bio-oil (including viscosity) and biochar were also discussed.

A. EFFECT OF TEMPERATURE ON PRODUCT YIELD

Previous studies showed that maximum yield of bio-oil (on different types of biomass) can be produced between 450 to 500^{o}C [15, 17, 23, 55-56]. Hence, four different temperatures were selected in between 425 to 500^{o}C (such as 425, 450, 475, 500^{o}C) to determine an optimum temperature for maximum bio-oil production. As stated in the Section 6.1, each biomass (pinewood, underutilized forest biomass and poultry litter) was processed at each temperature for three iterations in order to comprehend their behavior statistically. Figure 24 (refer Appendix B.1) shown below represents the yield of bio-oil obtained from processing pinewood, underutilized forest biomass and poultry litter, and the values corresponds the average yield of various products obtained from three iterations.

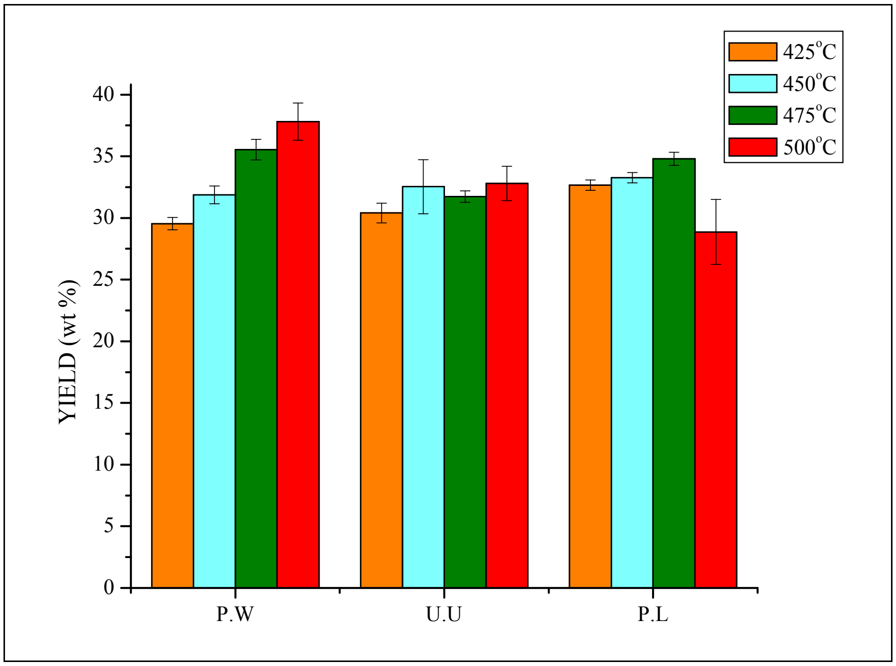

Figure 24: Yield of bio-oil from selected biomass at different temperatures

Here, X-axis of the graph represents the different types of bio-oil (in which P.W. represents pinewood, U.U. represents underutilized forest biomass and P.L. represents the poultry litter), and the Y-axis represents the yield (in wt %) of bio-oil. As specified in the graph orange, cyan, green and red bars represent the operating temperature of the process (425, 450, 475 and 500 °C, respectively).

Table 7: P-values of the various products of selected biomass

Type of biomass	**P-value of the products**		
	Bio-oil	**char**	**Gas**
Pinewood	0.0002	<0.0001	<0.0001
Underutilized forest biomass	0.2202	0.0151	0.0279
Poultry litter	0.0044	<0.0001	<0.0001

From Figure 24, the yield of bio-oil obtained from pinewood biomass increases with increase in operating temperature and it was noticed that maximum yield of bio-oil (37.8 wt %) was obtained at 500°C. The ANOVA analysis (as shown in Table 7, refer Appendix B.1) at 95%

confidence interval showed that operating temperature of the process (in the range of 425-500^{o}C) plays a significant role (p-value = 0.0002) in bio-oil production (from pinewood biomass). Horne and Williams (1996) and Demirbas (1998) have mentioned that as the operating temperature of the process increases bio-oil production also increases, (while processing mixed wood waste as the feedstock) [16, 18]. However, previous studies have reported an optimum temperature for maximum bio-oil production and any further raise in the operating temperature results in less bio-oil yield (irrespective of biomass) [15, 23, 56].

The yield of bio-oil obtained from underutilized forest biomass fails to show a similar trend like pinewood biomass, and it was also noticed that bio-oil yield was steady for all the operating temperatures (as the bio-oil yield was between 30.4 – 32.8 wt % irrespective of operating temperature). In addition, ANOVA analysis also showed that there was no significant change (P-value = 0.2202) on bio-oil yield with respect to the operating temperature ranging between 425 to 500^{o}C. Pyrolysis of poultry litter shows that the yield of bio-oil increases with increase in operating temperature and maximum bio-oil production (34.8 wt %) was achieved at 475^{o}C. The ANOVA analysis reports that there is a significant change (p-value = 0.0044) in bio-oil production with respect to temperature operated in between 425-500^{o}C. However, the yield of bio-oil decreases (at 500^{o}C) while processing the biomass higher than its optimum temperature for bio-oil production. Similarly, Kim et al. (2009), Jung et al. (2008), and Lee et al. (2008) reported that biomass such as bedding, chicken litter (flock 2, broiler), rice straw, and many more show a decreasing trend in bio-oil yield after processing them at higher temperatures (500-550^{o}C) [19, 56-57].

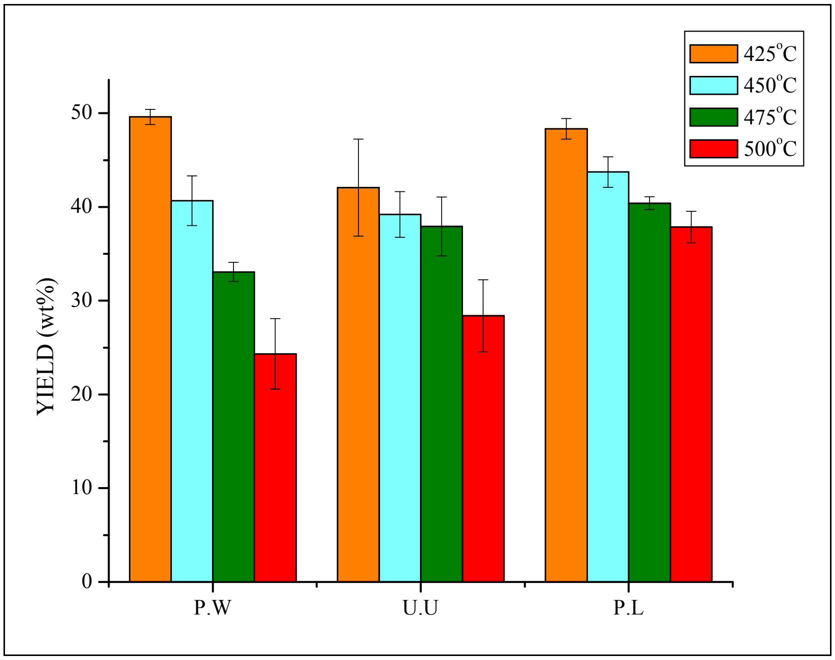

Figure 25: Yield of biochar from selected biomass at different temperatures

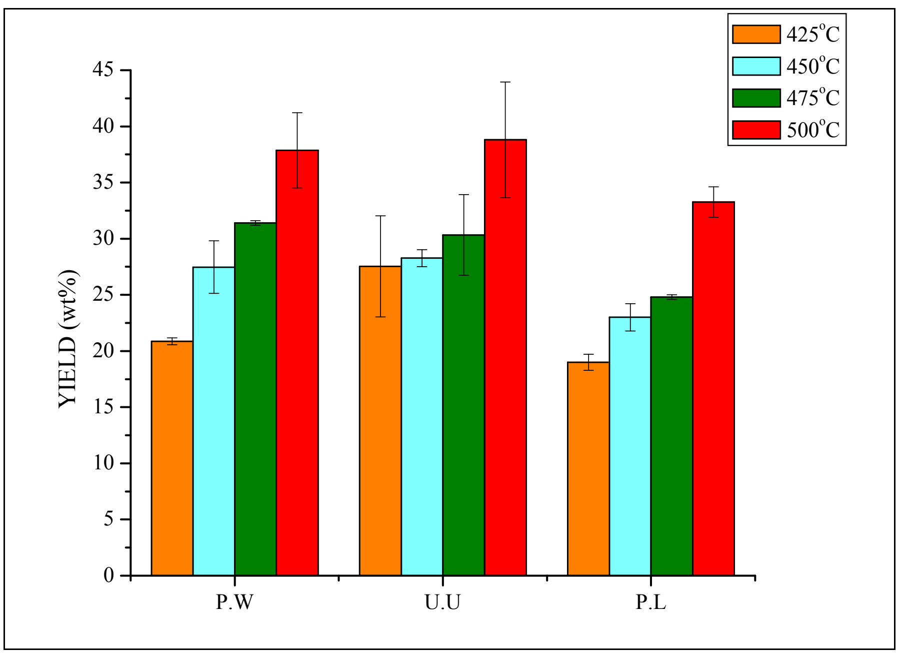

Figure 26: Yield of gases from selected biomass at different temperatures

In Figures 25 and 26 (refer Appendix B.1), X-axis of the graph represents the different types of biochar and gas and the Y-axis represents the yield (in wt %) of biochar and gas, respectively. As specified in the graph orange, cyan, green and red bars represent the operating temperature of the process (425, 450, 475 and 500 ^{o}C, respectively).

From Figures 25 and 26, it was evident that as the operating temperature of the process increases (irrespective of the biomass), the yield of biochar decreases; whereas the gas yield increases. For pinewood and poultry litter, the char yield decreases gradually while increasing the temperature and a similar trend in opposite direction (gas yield increases while increasing the temperature) was observed for the gas. For underutilized forest biomass, the char yield decreases gradually from 450-475^{o}C and abruptly thereafter (which results in high gas yield at 500^{o}C). ANOVA analysis was also performed on the biochar and gas yields data. The p-values for biochar and gas yields (as shown in the Table 7, refer Appendix B.1) on char and gas confirmed that the temperature has significant effect on their yields for all selected feedstock.

From previous studies [58-60], using auger reactor, it was found that as the operating temperature increases the bio-char yield decreases which corresponds to high gas yield. Similar trend was also observed while processing different types of biomass in other types of reactors such as fixed bed and fluidized bed [15, 23, 55-56]. For instance, Ingram et al. (2008), Asadullah et al. (2007), and Kim et al. (2009) reported that as the operating temperature increases the yield of bio-char decreases and the gas production increases, irrespective of the biomass and the reactor used. Previous studies mentioned that primary decomposition of biomass takes place at lower pyrolysis temperature and as the operating temperature increases; the pyrolytic vapors were further cracked down into low molecular weight organic compounds and gaseous products (non-condensable gases) which results in high gas yield [15, 23].

B. EFFECT OF TEMPERATURE ON PHYSICAL PROPERTIES OF BIO-OIL

This section depicts all the physical properties of the bio-oil produced from pinewood, underutilized forest biomass and poultry litter at four different temperatures. Basically, this section is further divided into three parts (based on the feedstock) in order to understand (easy and also in a better way) the effect of temperature on different properties of bio-oil, easily and thoroughly.

B.1 EFFECT ON PINEWOOD BIO-OIL

Different physical properties (such as density, pH, calorific value, water content, solid content and ash content) of pinewood bio-oil were measured to characterize them against different operating temperatures and the values of those properties were summarized in Table 8 (refer Appendix B.2, Table B.2.1-B.2.6) as shown below.

Table 8: Physical properties of bio-oil produced from pinewood at different temperatures†.

Properties	**Pyrolysis Temperature , °C**				**p-value from ANOVA test**	**ASTM Std D 7544-09**
	425	**450**	**475**	**500**		
Density, kg/m^3	1152 ± 8	1149 ± 13	1134 ± 22	1131 ± 21	0.0305	1100-1300
pH	3.33 ± 0.02	3.43 ± 0.04	3.67 ± 0.03	3.73 ± 0.03	<0.0001	Report
Water, wt%	19.67 ± 1.8	19.27 ± 1.4	18.39 ± 1.1	17.23 ± 1.2	0.4074	30 max.
HHV, MJ/kg	19.95 ± 0.7	20.85 ± 0.6	21.25 ± 0.4	22.02 ± 0.5	<0.0001	15 min.
Ash, wt%	0.61 ± 0.1	1.003 ±0.2	0.856± 0.1	0.33 ± 0.1	<0.0001	0.25 max.
Solid, wt%	0.63 ± 0.1	0.55 ± 0.1	0.66 ± 0.1	0.59 ± 0.2	0.4858	2.5 max.

† Values are means of nine repeated analysis and the numbers after ± is standard deviation.

Table 8 consists of different physical properties of bio-oil obtained from pinewood biomass along with ASTM standard D 7544-09 [61] of bio-oil (in order to compare the results obtained from the analysis). In addition, average and standard deviation of the experiments were calculated and ANOVA test (at, 95% confidence interval) was performed to determine the p-value for null hypothesis. The null hypothesis states that the average of each property at four different temperatures would be same. If the p-value > 0.05, the null hypothesis is true; whereas, if the p-value < 0.05 then the given data failed to prove the null hypothesis; and therefore, there is a change in the property with the temperature.

From the above table, it was clear that the density of bio-oil decreases with increase in operating temperature because of further breakdown of large molecules into low molecular weight compounds at higher temperature [17]. Further, p-value obtained from ANOVA analysis depicts that there was a significant change in the density of bio-oil while changing the temperature. Similar trend (decrease in density of bio-oil with increase in temperature) on the density of bio-oil was observed from the previous studies [17, 23]. Convincingly, the values of Thangalazhy-Gopakumar et al. (2010) reported that there was a significant change (P-value = 0.0594) in density with increase in temperature [23]. In addition, several studies have recorded slightly higher values of density when compared to the density of pinewood measured in this work [14, 23].

Acidity of bio-oil decreases (as the pH value increases) with the increase in operating temperature, and the maximum pH value (3.73) was obtained at 500^{o}C, however Mohan et al. (2006) and Thangalazhy-Gopakumar et al. (2010) recorded less pH (around 2.3-2.4) when compared to this work. Statistically, ANOVA analysis confirms that the operating temperature has a significant effect on pH value. However, petroleum fuels have wide and strong applications compared to bio-oil because petroleum fuels are not as acidic; whereas bio-oils are more acidic. Therefore, bio-oils are not widely used as a primary fuel in the automobile engines.

From Table 8, water content of the bio-oil (pinewood) decreases with increase in operating temperature but statistically, there was no significant change. However, Thangalazhy-Gopakumar et al.(2010) reported that water content of bio-oil (pinewood) remains constant at different operating temperatures [23]. Higher heating value (HHV) of bio-oil increases with the increase in temperature and statistically, ANOVA analysis reports that the operating temperature has a significant effect on heating value of the bio-oil. However, previous studies have not recorded similar kind of results to emphasize this effect [17, 23]. Certainly, heating value of bio-oil recorded in this work was higher when compared to other studies made on pinewood biomass [14, 23]; however these values were much lower than the petroleum fuels (40MJ/kg, Table 4).

Solid content of pinewood bio-oil was constant (0.55-0.63 wt %) at different temperatures and ANOVA analysis also depicts that operating temperature had no significant effect on solid content. Similarly, He et al. (2009) reported that solid content of bio-oil obtained from switchgrass (at 5% moisture content) had no effect on temperature [17]. It was also noted that all the properties of the bio-oil reported in this section meet the ASTM standards except ash content. Ash content of the bio-oil was high at 450^{o}C and drops down thereafter but statistically, temperature had a significant role in the ash content of the bio-oil. Nevertheless, Thangalazy – Gopakumar et al. (2010) reported that the ash content was constant at different temperature, and statistically there was no significant change [23]. Further, rationale behind the presence of high ash content and removing them from bio-oil are yet unknown.

B.2 EFFECT ON UNDERUTILIZED FOREST BIO-OIL

The values of the physical properties of bio-oil produced from underutilized forest biomass at four different temperatures were summarized in Table 9 (refer Appendix B.2, Table

B.2.7-B.2.12). The table also shows how a comparison of these values to the corresponding values from ASTM standard D 7544–09 [61].

Table 9: Physical properties of bio-oil produced from underutilized forest biomass at different temperatures†.

Properties	Pyrolysis Temperature , °C				p-value from ANOVA test	ASTM Std D 7544-09
	425	450	475	500		
Density, kg/m^3	1188 ± 17	1185 ± 10	1181 ± 11	1170 ± 10	0.0267	1100-1300
pH	2.93 ± 0.06	2.97 ± 0.07	3.04 ± 0.04	3.09 ± 0.07	<0.0001	Report
Water, wt%	18.19 ± 1.8	18.05 ± 1.5	17.38 ± 1.4	17.59 ± 0.9	0.6082	30 max.
HHV, MJ/kg	19.53 ± 1.1	20.50 ± 0.6	20.42 ± 0.8	19.69 ± 1.1	0.0662	15 min.
Ash, wt%	0.93 ± 0.3	0.71 ±0.2	1.06± 0.2	0.62 ± 0.1	<0.0001	0.25 max.
Solid, wt%	0.28 ± 0.1	0.42 ± 0.1	0.53 ± 0.1	0.51 ± 0.1	<0.0001	2.5 max.

† Values are means of nine repeated analysis and the numbers after ± is standard deviation.

From Table 9, it appears that the density of bio-oil decreases as the operating temperature increases and statistically, ANOVA analysis depicts that density of bio-oil changes significantly with the operating temperature. This trend was similar to the trend obtained from pinewood bio-oil (produced for this work) and as mentioned before, study from Thangalazhy- Gopakumar et al.(2010) and He et al. (2009, at 5% moisture content) also highlighted the same results [17, 23]. Certainly, the density of bio-oil produced from pinewood and underutilized forest biomass recorded higher values when compared to the density of petroleum fuels (0.94 kg/m^3). Also, temperatures investigated in this study did not have any influence on water content and HHV (as their values are almost constant/same throughout working temperature) of the bio-oil. This analysis coincided with the study from Thangalazhy-Gopakumar et al.(2010) while using pinewood as the biomass [23]. In addition, Garcia-Perez et al. (2010) had recorded similar values (18 wt % of water content at 500^{o}C) while working on pinewood pellets [59].

He et al. recorded that pH value of bio-oil increases while increasing the temperature of the process and this coincides with the trend obtained from the pinewood bio-oil (produced for this work) [17]. In spite of observing similar results with the previous study, the pH value of bio-oil obtained from underutilized forest biomass was lower than the bio-oil obtained from pinewood biomass (produced for this work). On the other hand, solid content of the bio-oil increases gradually while increasing the temperature (upto 475^{o}C) and then reduces slightly. The rationale behind this fact is, increasing the operating temperature of the process results in producing the fumes (gases, aerosols and burnt biomass/char) of higher velocity due to its decreased production rate. Further, when these fumes are passed into the heat exchanger for condensation; char particles present in the fumes are damped and collected along with the previously condensed bio-oil and thus increase in solid content with increase in operating temperature. However, ANOVA analysis states that the solid content of the bio-oil changes significantly while changing the temperature and convincingly, statistical records of Thangalazhy – Gopakumar et al. (2010) supports this fact [23]. Further, ash content of the bio-oil was higher than the ASTM standard and the reason behind this large numbers could be due to soil and sand particles (less than 1μm size) entrained with the bio-oil vapor during the pyrolysis process.

B.3 EFFECT ON POULTRY LITTER BIO-OIL

The values of the physical properties of the bio-oil produced from poultry litter biomass at four different temperatures were summarized in Table 10 (refer Appendix B.2, Table B.2.13-

B.2.18). ASTM standard D 7544–09 was also included in this table for comparing their corresponding results obtained in this work [61].

Table 10: Physical properties of poultry litter bio-oil produced at different temperatures†.

Properties	Pyrolysis Temperature , °C				p-value from ANOVA test	ASTM Std D 7544-09
	425	450	475	500		
Density, kg/m^3	1081 ± 40	1064 ± 15	1063 ±11	1062 ± 3	0.2399	1100-1300
pH	9.2 ± 0.02	9.3 ± 0.01	9.3 ± 0.02	9.4 ± 0.06	<0.0001	Report
Water, wt%	34.86 ± 2.22	30.75 ± 2.4	29.18± 1.89	29.09 ± 1.89	<0.0001	30 max.
HHV, MJ/kg	11.19 ± 0.54	12.46 ± 0.78	14.18± 0.38	13.89 ± 0.45	<0.0001	15 min.
Ash, wt%	0.099 ± 0.02	0.168 ± 0.02	0.201 ± 0.01	0.147 ± 0.12	<0.0001	0.25 max.
Solid, wt%	0.10 ± 0.02	0.14 ± 0.03	0.25 ± 0.08	0.17 ± 0.05	<0.0001	2.5 max.

† Values are means of nine repeated analysis and the numbers after ± is standard deviation.

Similar to pinewood and underutilized forest bio-oil, density of poultry litter bio-oil (shown in Table 10) also decreases with the increase in temperature but statistically, there was no significant change. He et al., (2009, at 10% moisture content) had also supported this fact statistically while processing switchgrass as the feedstock in pilot fluidized bed reactor [17]. Though the density of bio-oils produced from woody biomass changes significantly (as per ANOVA analysis) with respect to temperature, their values meet the ASTM standards; whereas the density of bio-oil produced from poultry litter fails to meet the same.

From Table 10, it was evident that all the properties of poultry litter bio-oil (except density) changes significantly with respect to temperature. Basically, pH value of poultry litter bio-oil increases with increase in temperature and this coincides with the bio-oils obtained from the woody biomass (investigated in this work). Certainly, poultry litter bio-oil has higher pH value (9.4 at 500°C) when compared to other bio-oils produced in this work (pinewood and underutilized forest bio-oil). In addition, several studies [62-65] were made on other woody biomass such as cassava plants, rice husks, sugarcane waste and sugarcane bagasse using different reactors (fluidized bed and fixed bed) to determine the pH value of their respective bio-oil, and it was observed that the pH value of all those bio-oils were between 2.8 to 3.85.

In this work, all the properties of the bio-oil were measured without separating water contained in the bio-oil. Particularly, poultry litter bio-oil has more water content when compared to the other bio-oils produced in this work and this is due to the presence of high moisture content in poultry litter (12.76 wt %) biomass when compared to other woody biomass. Generally, during the process, moisture contained in the biomass are converted in the form of steam and collected as water molecules in bio-oil during condensation [66-67]. However, reason behind high moisture content in bio-oil obtained while processing the biomass at 425°C was unknown. Eventually, high water content reduces the heating value of the bio-oil, and hence its HHV were low while comparing to the bio-oil produced from other woody biomass. Kim et al. (2009) reported that the heating value of bio-oil obtained from poultry litter bedding was 18.11 MJ/kg, however, the moisture content of the biomass was less (8.08 wt %) when compared to the poultry litter used in this study [56]. Nevertheless, in this study the heating value of the bio-oil obtained from poultry litter did not meet the ASTM standard.

Ash and solid content of poultry litter bio-oil increase while increasing the operating temperature (till 475°C) and reduce thereafter, and statistically it was reported that the values of the above properties change significantly with respect to temperature. However, they drop after 475°C. A similar trend was also observed while processing broiler chicken litter as the feedstock in a fluidized-bed reactor [56]. Kim et al. (2009) reported that the ash content of the poultry litter bedding biomass was measured almost similar to the ash content (of poultry litter bio-oil) observed in this work (0.1 wt % at 500°C) [56]. Solid content of the poultry litter bio-oil records lower values when compared to other bio-oils produced in this work. As a whole, all the properties of poultry litter bio-oil meet the ASTM standard except density and heating value.

C. MULTIPLE COMPARISON ANALYSIS

This section comprises of multiple comparison analysis made on the effect of different types of biomass and operating temperatures over the yield of various products of the pyrolysis process, and the physical properties of bio-oil and biochar. In this analysis, two way ANOVA (at 95%, confidence interval) was performed using Minitab software (refer Appendix B.5).

From this analysis, it was evident that yield of bio-oil and char changes significantly for different biomass, operating temperature, and during their interaction. In addition, high yield of bio-oil was obtained while processing pinewood at 500 °C. Further, gas yield changes significantly while executing the process at different biomass types, and operating temperature. However, no significant change in gas yield was observed during the interaction of the controllable factors (biomass type and temperature).

Apart from this, pH, heating value, solid and ash content of the bio-oil changes significantly for different controllable factors, and also during their interaction. Further, poultry litter bio-oil has higher pH value and lower solid content when compared to the bio-oils obtained from the woody biomass. Certainly, heating value of pinewood bio-oil obtained from 500 °C was higher than the bio-oil obtained from other biomass. Apparently, density of bio-oil changes significantly for different biomass and operating temperature. However, no significant change was observed during their interaction. Simultaneously, water content of bio-oil changes significantly only at different biomass types and not during temperature change, and during their interaction (biomass type and temperature). However, poultry litter bio-oil has high water content when compared to the bio-oils obtained from woody biomass.

Two way ANOVA analysis also depicts that heating value, ash and moisture content of biochar changes significantly at different controllable factors, and also during their interaction. In addition, poultry litter biochar has high amount of ash content and pinewood biochar has high heating value when compared to other biochar analyzed in this study.

D. VISCOSITY ANALYSIS OF DIFFERENT BIO-OILS

Kinematic viscosity is a significant property of fuels. The consequences of higher viscosity values correspond to complicated design, complex handling, processing and transporting the equipment. In this study, the viscosity analysis on bio-oils (obtained from different biomass at 500°C) was carried out at 40°C and their results were shown in the Figure 27 (refer Appendix B.3).

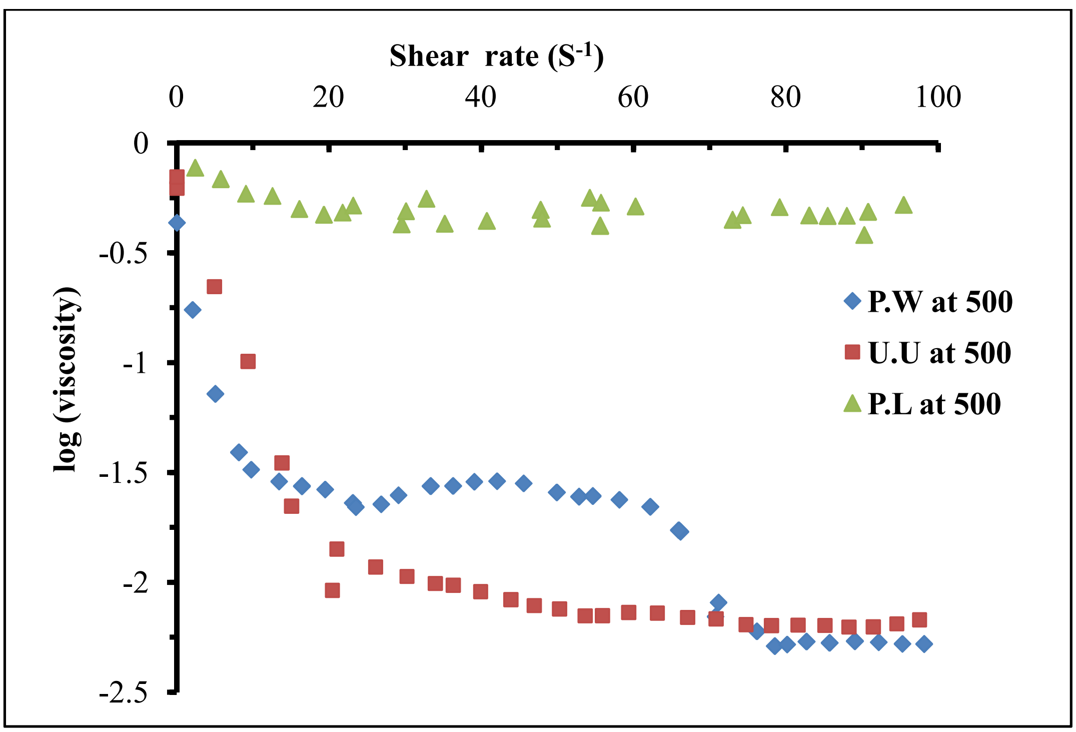

Figure 27: Viscosity analysis on different bio-oils

From Figure 27, it was evident that viscosity analyses were made on different bio-oils obtained from pinewood (P.W), underutilized forest biomass (U.U) and poultry litter (P.L). Further, X-axis of the graph represents shear rate (S^{-1}) of the bio-oil and the Y-axis represents the viscosity of bio-oil in logarithmic scale. From previous studies [23, 56, 68] it was observed that after a particular shear rate, viscosity of bio-oils produced from different operating temperatures behaves similarly (with respect to values of viscosity). This helped in narrowing the analysis from four different temperatures to one temperature (500°C) and the rationale behind this temperature selection was due to high bio-oil yield (from pinewood biomass) and high pH value.

Fuels like gasoline (0.006 Pa.s) and diesel (0.011Pa.s) are less viscous when compared to bio-oil. From Figure 27, it is evident that poultry litter bio-oil is more viscous than other bio-oils produced from woody biomass, and the viscosity of this bio-oil was constant at higher shear rate (< $30S^{-1}$). Further, between shear rate < $20S^{-1}$ and > $80S^{-1}$, viscosity of pinewood bio-oil is higher than underutilized forest bio-oil. In addition, viscosity of pine wood bio-oil varies at higher shear rates whereas, viscosity of underutilized forest bio-oil was almost constant at shear rate < $60S^{-1}$.

E. EFFECT OF TEMPERATURE ON BIOCHAR

There is now an increase interest in bio-char obtained from fast pyrolysis because bio-char sequestration makes the biomass to bioenergy conversion process via pyrolysis a carbon negative process [69]. Basically, this section comprises of the effect of temperature on various physical properties of biochar obtained from processing different biomass. In addition, ANOVA analysis at 95% confidence interval was also carried out on all the physical properties of bio-char (measured in this work). Tables 11, 12 and 13 (refer Appendix B.4) show the characterization of bio-char (pinewood, underutilized forest biomass and poultry litter respectively) obtained from four different temperatures for heating value, ash and moisture content.

Table 11: Physical properties of pinewood biochar produced at different temperatures†.

Properties	Pyrolysis Temperature				p-value from ANOVA Test
	425°C	450°C	475°C	500°C	
HHV, MJ/kg	25.97 ± 0.75	26.81 ± 0.85	29.04 ± 0.58	30.45 ± 0.36	<0.0001
Ash, wt%	0.69 ± 0.14	1.13 ± 0.22	0.884± 0.18	0.51 ± 0.22	<0.0001
Moisture content, wt%	2.76 ± 0.09	3.14 ± 0.15	3.31 ± 0.51	3.64 ± 0.25	<0.0001

† Values are means of nine repeated analysis and the numbers after ± is standard deviation.

Table 12: Physical properties of underutilized forest biochar produced at different temperatures†.

Properties	Pyrolysis Temperature				p-value from ANOVA Test
	425°C	450°C	475°C	500°C	
HHV, MJ/kg	23.08 ± 0.64	23.65 ± 0.93	23.86 ± 0.51	25.95 ± 0.47	<0.0001
Ash, wt%	2.04 ± 0.27	2.74 ± 0.44	2.97 ± 0.77	3.43 ± 0.74	<0.0001
Moisture content, wt%	1.13 ± 0.39	0.56 ± 0.43	0.77 ± 0.44	0.83 ± 0.53	0.0779

† Values are means of nine repeated analysis and the numbers after ± is standard deviation.

Table 13: Physical properties of poultry litter biochar produced at different temperatures†.

Properties	Pyrolysis Temperature				p-value from ANOVA Test
	425°C	450°C	475°C	500°C	
HHV, MJ/kg	12.15 ± 0.29	11.16 ± 0.38	11.05± 0.36	10.81 ± 0.29	<0.0001
Ash, wt%	47.78± 5.01	56.48 ± 1.06	57.45 ± 1.4	58.76 ± 2.54	<0.0001
Moisture content, wt%	3.13 ± 0.65	2.61 ± 0.99	3.27 ± 0.95	3.69 ± 0.76	0.0801

† Values are means of nine repeated analysis and the numbers after ± is standard deviation.

From the above tables (Table 11,12, and 13), statistically, it was found that heating value and ash content of all the biochar obtained from processing different biomass had shown a significant change with respect to the increase in pyrolysis temperature. Similar trend was also noticed from the study reported by Thangalazy-Gopakumar et al. (2010) [23]. Eventually, the values of moisture content in poultry litter and underutilized forestry biochar were not significant with respect to operating temperature; however, the moisture content of pinewood bio-char showed its significance on temperature.

It was also noticed that as operating temperature increased the heating value of pinewood and underutilized forestry biochar also increased. Certainly, pinewood biochar have recorded higher heating value (30.45MJ/kg at 500°C) than all the other biomass used in this study. However, the heating value of pinewood biochar was low while comparing with the other studies made on radiata pine sawdust biomass (29.9 MJ/kg at 400°C in a bubbling fluidized bed reactor) [21]. Particle size used in that study was finer (0.7mm) when compared to the particle size of biomass used in this work. Hence at certain operating temperature, biomass of smaller particle size can produce bio-char of higher heating values. In addition, Jung et al. reported that the bio-char (rice straw as feedstock) obtained at 490°C gave the maximum heating value of 17 MJ/kg [57].

The heating value of poultry litter biochar decreases with the increase in temperature and this is due to the fact that at higher operating temperatures amount of ash contained in the biochar increases. Hence, at higher operating temperature, poultry litter biochar has poor heating value. However, the bio-char can be used as an auxiliary source in energy production (solid fuel) due to its high heating value, further it is also used for soil amendment and to reduce the greenhouse gas emissions [21, 70].

7.1.4 CONCLUSIONS

This section contains the most important conclusions made on the results obtained from the above experiments. In addition, it also reviews the reasons behind the selection of different operating parameters involved in the upcoming objectives. From this objective, it was noticed that maximum amount of bio-oil (37.8 wt %) was produced while processing pinewood at 500°C, whereas other biomass produces less yield of bio-oil (underutilized forest biomass: 32.5 wt% at 450°C, and poultry litter: 34.8 wt% at 475°C).

Eventually, these observations helped in selecting pinewood and 500°C as the primary biomass and operating temperature for the next objective (Production of bio-oil using sacrificial bio-based additive). However, poultry litter was selected as the secondary biomass because the pH value of bio-oil obtained from poultry litter (9.4) was higher than the bio-oils obtained from other woody biomass. Thus, to meet our objective (to increase the pH value of bio-oil) above parameters were followed for the second objective, and for the third objective, 500°C was selected as the operating temperature (at second stage). Apart from this, all most all the physical properties of the bio-oil obtained in this study met the ASTM standards (except ash content of bio-oil obtained from woody biomass and density, and heating value of poultry litter bio-oil).

7.2 PRODUCTION OF BIO-OIL USING SACRIFICIAL BIO-BASED ADDITIVE

This work was the first step towards the production of high pH value bio-oil using two different types of biomass. As the pH value of the poultry litter bio-oil (obtained from the previous objective) was really high (9.4, basic and not acidic) when compared to the bio-oil obtained from woody biomass, here, poultry litter was used as an additive with pinewood so that the basic compounds of the poultry litter react with the acidic compounds of the pinewood, thereby increasing the pH of the bio-oil. Further, this Section also includes the general information about poultry litter, reasons for using poultry litter as an additive, ideas followed and their consequences.

7.2.1 SUMMARY

Bio-oil has numerous applications in various fields such as energy production, IC engines, producing chemicals and in food industry. However, most of its applications are limited by its negative attributes such as acidity, high oxygen content, storage instability and few more. In this work, we considered acidity as the major drawback for limiting its (bio-oil) applications. Hence, cheap and simple methods have been tried here to improve the pH value of the bio-oil so that it can be used in the current refineries without or less upgrading. Here, pinewood (primary biomass) and poultry litter (secondary biomass) were mixed at different proportions (5, 10, 15 % of poultry litter in 95, 90, 85 % of pinewood, respectively) and they were processed at 500°C (with reference to the remarks made from the results of the previous objective) to understand their effect on pH value of the bio-oil. Physical properties of bio-oil obtained after processing various proportions of different biomass were measured and compared with the ASTM standards (to document the effect of pyrolysis temperature). All the properties of the bio-oil, analyzed in this study, met the specifications suggested by the ASTM standard except ash content. In addition to the above analysis, kinematic viscosity of bio-oil was also measured. Furthermore, physical properties of biochar were measured and analyzed.

7.2.2 INTRODUCTION

In animal operations, animal wastes are obvious and they are impossible to eliminate those wastes from the system. Especially in poultry wastes, USA is the biggest producer of poultry litter in the world and this includes both broiler and turkey litter [54]. In US, Alabama state was the third largest producer (in 2009) of poultry litter and Alabama Co-operative Extension System states that in 2008, nearly 1.8 million tons of poultry litter was produced, and it is estimated to reach 2 million tons by 2011 [71-72].

Basically, poultry litter consists of various elements such as manure, bedding material, feathers and spilled feed of chicken, in which the bedding materials may contain wood shavings, peanut, rice hulls, dirt on the floor and shredded paper products [73-76]. In addition, the composition of poultry litter produced in the farms may vary according to the quantity of chicken raised in the farm, type of bedding material used, water system, clean out process, storage time and few more [74, 77].

Generally, poultry litter is used as a substitute for fertilizer because of the amount of inorganic matter contained in it [77] and in Alabama, the production of poultry litter is three times more than the amount of fertilizer required for the state [72]. Eventually, interest on land disposal of poultry wastes results in runoffs rich in nutrients and this spoils the water resources. Further, surplus use of poultry litter in land application leads to cancer, respiratory illness in humans and fetal abortions in livestock [75, 78]. In addition, it (poultry litter) is also used as a feed for beef cattle [75] thereby, it solves various problems such as, reducing the problematic wastes, provides an incentive for the proper management of this by-product of poultry and cattle producers and economizes the beef cattle production .

High production of poultry litter and its effect of various environmental issues encouraged several researchers and scientist to use this waste in energy production methods such as direct combustion, anaerobic digestion and gasification [54, 75, 78-79]. In addition, Koutcheiko et al. (2007) processed chicken manure through pyrolysis process. Similarly, in this work, poultry litter and pinewood mixtures were fast pyrolysed at 500°C [80]. In this objective, as mentioned above, three different proportions of poultry litter (with pinewood) were investigated at fixed temperature (as high yield of pinewood bio-oil was produced at 500°C). Under each operating condition, three iterations were executed to understand the effect of poultry litter contained in pinewood, statistically.

7.2.3 RESULTS AND DISCUSSIONS

In this section, the yield of different products obtained from processing different biomass mixture (at fixed operating temperatures, 500^{o}C) was reported. In addition, different physical analysis of bio-oil (including viscosity) and biochar were also discussed here.

A. EFFECT OF ADDITIVE ON PRODUCT YIELD

From previous objective, we confirm that high bio-oil production was obtained from processing pinewood biomass, and high pH value of bio-oil was obtained while processing poultry litter. Hence, we tried to use both the biomass (as a mixture) to obtain high quantity of bio-oil with high pH value. Here, poultry litter is mixed with pinewood at 5, 10, 15 wt% in order to comprehend the behavior of the mixture (while processing), and to determine the optimum proportion (of poultry litter with pinewood) at which high pH value of bio-oil was obtained.

Hence, the mixture was processed at 500°C (temperature at which maximum pinewood bio-oil was produced) to determine an optimum proportion of mixture for maximum bio-oil production and high pH value. As stated in the previous Section 6.1, each type of mixture was processed thrice at fixed temperature in order to comprehend their behavior statistically. Figure 28 (refer Appendix C.1) shown below represents the yield of bio-oil, biochar and gases from the various proportion of pinewood, and poultry litter biomass and the values corresponds the average yield of various products obtained from three replications.

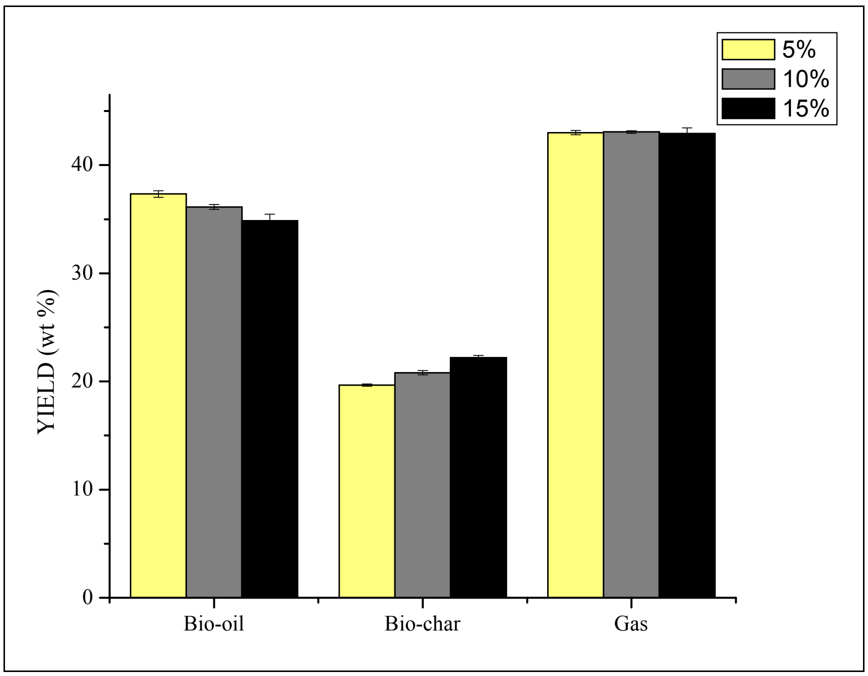

Figure 28: Product yield of different biomass mixtures at 500°C

Here, X-axis of the graph represents different products of the process and the Y-axis represents yield (in wt %) of different products. As specified in the graph, yellow, grey and black bars represent the various proportions of poultry litter in pinewood.

Table 14: P-values of the different products of selected biomass

Type of biomass mixtures	P-value of the products		
	Bio-oil	char	Gas
0, 5, 10, 15, 100 wt % of P.L with 100, 95, 90, 85, 0 wt% of P.W	<0.0001	<0.0001	<0.0001

From Figure 28, it was evident that as the proportion of poultry litter (additive) in pinewood increases, the yield of bio-oil decreases at fixed operating temperature (500 ^oC). It was also noticed that the maximum yield of bio-oil (37.3 wt %) was obtained at 5 wt % of poultry litter with pinewood and minimum yield of bio-oil (34.8 wt%) was obtained at 15 wt% of poultry litter. From Table 14 (refer Appendix C.1), ANOVA analysis at 95% confidence interval reveals that different proportion of poultry litter in pinewood plays a significant role (p-value = 0.0011) in bio-oil production. Mante and Agblevor (2010) mentioned a similar trend (with respect to bio-oil production) while processing poultry litter (broiler and turkey litter) with pinewood shavings [77]. In their study, they investigated the mixture at 100, 75, 50, 25, 0 wt % of pine wood with poultry litter and recorded that as the weight proportion of pinewood decreases, the yield of bio-oil also decreases. In addition, Mante and Agblevor (2010) mentioned that maximum yield of bio-oil was obtained at 25 wt% of poultry litter (i.e., 75 wt % of pinewood), and it was nearly 53.5 wt% of bio-oil yield at 450^oC. However, while comparing the current results of bio-oil yield with the previous objective, the yield of bio-oil obtained at 100% pinewood was about 37.8 wt% whereas the yield of bio-oil was 37.3 wt% at 95% of pinewood. Hence, it was observed that there was no significant difference in the yield of bio-oil while adding poultry litter in small quantities, however, it (poultry litter) affects the bio-oil yield while increasing the proportion of poultry litter in pinewood

From Figure 28, it was apparent that increasing the proportion of poultry litter in pinewood results in increasing the yield of biochar obtained from the process, and it was due to the high amount of ash contained in the poultry litter biomass. The ANOVA analysis also showed that (from Table 14), quantity of biochar changes significantly (p-value = <0.0001) while changing the proportion of poultry litter in pinewood. Similarly, study of Mante and Agblevor (2010) also reported a similar trajectory on biochar production while processing the mixture in a fluidized bed reactor [77]. Apparently, the gas yield did not show any kind of major differences while processing at different proportion of additive (poultry litter) with the primary biomass. Convincingly, Mante and Agblevor (2010) have also recorded no change on gas production while increasing the ratio of poultry litter in pinewood [77]. However, results obtained from the ANOVA analysis also mentioned that the yield of gas was significant with the addition of poultry litter in pinewood (Table 14).

B. EFFECT OF ADDITIVE ON PHYSICAL PROPERTIES OF BIO-OIL

This section comprises of the physical properties of bio-oil produced from different proportions of poultry litter (additive) with pinewood at fixed operating temperature. Basically, in this section the mixtures were compared with pure (100 wt %) poultry litter and pure pinewood biomass in order to understand the effect of poultry litter in pinewood.

Table 15: Physical properties of bio-oil produced from different proportions of poultry litter with pinewood at 500°C†

Properties	**Pine Wood (at 500°C)**	**Different additive ratios (wt %)**			**Poultry litter (at 500°C)**	**p-value from ANOVA Test**	**ASTM Standard D 7544-09**
		5%	**10%**	**15%**			
Density, kg/m^3	1131 ± 21	1122 ± 19	1116 ± 9	1101 ± 8	1062 ± 3	<0.0001	1100-1300
pH	3.73 ± 0.03	3.7 ± 0.02	3.84 ± 0.01	3.94 ± 0.01	9.43 ± 0.06	<0.0001	Report
HHV, MJ/kg	22.02 ± 0.51	21.25 ± 0.41	19.8 ± 0.38	17.99 ± 0.48	13.89 ± 0.45	<0.0001	15 min.
Ash, wt%	0.331 ± 0.11	0.399 ± 0.04	0.311 ± 0.04	0.371 ± 0.08	0.147 ± 0.12	<0.0001	0.25 max.
Solid, wt%	0.59 ± 0.25	0.59 ± 0.06	0.65 ± 0.08	0.86 ± 0.07	0.17 ± 0.05	<0.0001	2.5 max.
TAN No.	55.7 ± 0.1 (3.37)	41.4 ± 0.7 (3.5)	28.9 ± 0.9 (3.62)	27 ± 1.6 (3.73)	0 ± 0 (9.1)	<0.0001	Report

† Values are means of nine repeated analysis and the numbers after ± is standard deviation. The values shown along with TAN (in the brackets) represents the pH value of bio-oil measured at the time of determining Acid Number.

Different physical properties (such as density, pH, calorific value, water content, solid content and ash content) of the bio-oil were measured to characterize the effect of different proportions of poultry litter in pinewood and the values of those properties were summarized in the Table 15 (refer Appendix C.2) as shown above.

Table 15 depicts the various physical properties of bio-oil obtained from different ratios of additive (poultry litter) with pinewood biomass, and it also contains the ASTM standard D 7544-09 [61] of bio-oil in order to compare the results obtained from the analysis. In addition, average and standard deviation of the experiments were calculated and ANOVA test (95% confidence interval) was performed to determine statistical behavior of the different physical properties while changing the ratio of additive in primary biomass. It also includes physical properties of 100% pinewood and 100% poultry litter bio-oils obtained at 500°C for comparison.

From this table, it was evident that the density of bio-oil decreases while increasing the ratio of poultry litter in the primary biomass and this was due to the high moisture contained in poultry litter biomass. Apparently, ANOVA analysis also depicts that increasing the ratio of additive in primary biomass plays a significant role in the density of bio-oil. Certainly, pH value and water content of the bio-oil increases simultaneously while increasing the weight ratio of poultry litter in pinewood and p-value obtained from the ANOVA analysis also supports this fact. Here, raise in pH value was due to the high ash content of poultry litter which helps in cracking the fumes (produced during the process) and eventually producing high pH value bio-oil. Similarly, the increasing trend in water content of bio-oil was due to the amount of water molecules contained in the additive (later, they are moved to the bio-oil while condensing the fumes, vapors and aerosols). In addition, similar results (on pH value, density and water content) were observed from the previous study made on pinewood and poultry litter mixture [77].

On the other hand, solid content of bio-oil increases and heating value of the bio-oil decreases when higher proportions of poultry litter were added to the primary biomass. Certainly, heating value of bio-oil obtained from 15 % of poultry litter (17.99 MJ/kg) recorded lower values while compared with other bio-oils obtained from processing 5 and 10% of poultry litter, and this was due to the moisture content of poultry litter present in the biomass [81].

Theoretically, from Table 15, ash content of bio-oil should decrease while increasing the additive in primary biomass because the ash content of pure (100 wt %) pine wood bio-oil is higher than pure poultry litter bio-oil. However, it was not observed in this study and the reason behind this fact is mysterious. ANOVA analysis reveals that the quantity of poultry litter in pinewood plays a significant role in the values of heating value, ash and solid content. Incidentally, previous studies [77] have stated that both ash content and heating value (sample with the absence of water content) of the bio-oil increases with increase in poultry litter with pinewood, which was not observed in this study. From TAN (Total Acid Number) measurements, it was evident that as the composition of poultry litter increases in pine wood biomass, acid number of the bio-oil decreases. However, significant changes in pH value of bio-oil were not noticed during acidity measurement. This fact confirms that the amount of acids present in the bio-oil decreases significantly while increasing the amount of additive in primary biomass.

C. VISCOSITY ANALYSIS OF DIFFERENT BIO-OILS

As mentioned before, kinematic viscosity is a significant measure on fuel properties as higher viscosity values results in complicated design, requires complex handling, processing and transporting the equipment. In this study, the viscosity analysis on bio-oils obtained from different proportions of additive with primary biomass was carried out at 40°C and their results were shown in the Figure 29 (refer Appendix A.3 and C.3).

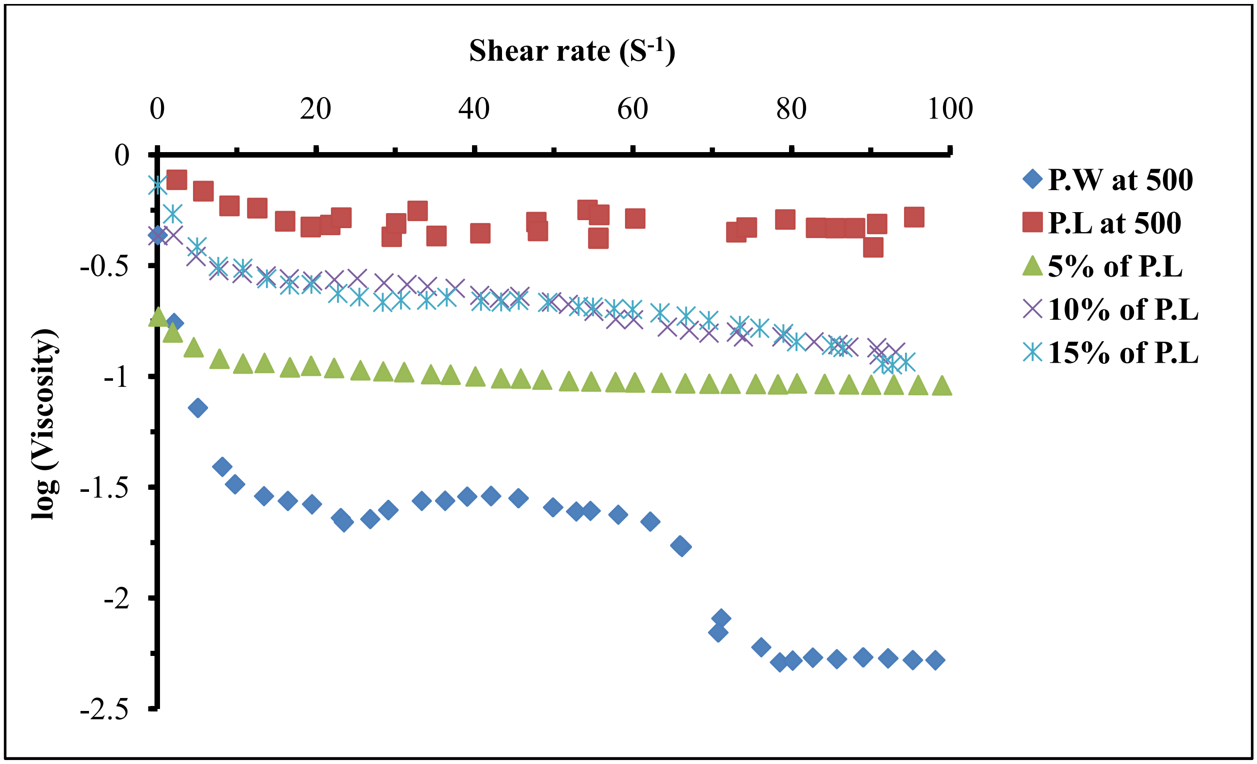

Figure 29: Viscosity analysis on different bio-oils

Figure 29 shows the various trends obtained while analyzing the dynamic viscosity of bio-oils obtained from processing different ratios of poultry litter with pinewood biomass. In addition, the dynamic viscosity of bio-oils obtained from both pinewood (P.W) and poultry litter (P.L.) (100% pure biomass) were also incorporated in this figure. However, from previous studies it was observed that after a particular shear rate viscosity of bio-oil produced at different operating temperatures behaves similarly (with respect to values of viscosity) [23, 56, 68]. All the trends (on dynamic viscosity) shown in the above figure were obtained from bio-oils collected while processing their respective biomass at 500°C.

Variation in log(viscosity) vs shear rate was shown in the above figure in which the shear rate was rated between 0.1 to 100 s^{-1}. As mentioned in the previous Section D. (under Section

7.1.3), viscosity of poultry litter bio-oil was higher than the viscosity of pinewood bio-oil, and from the above figure, viscosity of bio-oil increases while increasing the composition of additive in primary biomass. In addition, at shear rate <10 S^{-1}, viscosity of bio-oil obtained from processing 5 wt% of poultry litter was constant. However, other bio-oils obtained from 10 and 15 wt% of poultry litter experiences change in viscosity at higher shear rate.

D. EFFECT OF ADDITIVE ON PHYSICAL PROPERTIES OF BIOCHAR

Basically, this section comprises of the effect of different ratios of additive (contained in the primary biomass) on different physical properties of biochar. ANOVA analysis at 95% confidence interval was also carried out on the various properties of biochar. Table 16 shows the characterization on physical properties of bio-char (such as heating value, ash and moisture content) obtained from different proportions of additive in primary biomass.

Table 16: Physical properties of biochar produced from different additive ratios†

Properties	Pinewood (at 500°C)	Different additive ratios (wt %)			Poultry Litter (at 500°C)	p-value from ANOVA Test
		5%	10%	15%		
HHV, MJ/kg	30.45 ± 0.36	28.91 ± 0.3	27.24 ± 0.2	25.92 ± 0.3	10.81 ± 0.3	<0.0001
Ash, wt%	0.51 ± 0.22	8.76 ± 0.87	13.47 ± 1.25	15.86 ± 0.81	58.76 ± 2.54	<0.0001
Moisture content, wt%	3.64 ± 0.25	2.7 ± 0.4	2.84 ± 0.3	3.09± 0.4	3.69 ± 0.76	<0.0001

† Values are means of nine repeated analysis and the numbers after ± is standard deviation.

From Tables 16, the heating values of biochar obtained from different additive ratios state that as the poultry litter ratio increases in pinewood biomass (from 0 to 15 wt %), the heating value of the biochar decreases gradually (30 to 26 MJ/kg, from 0 to 10wt % of P.L in P.W). Certainly, in this objective biochar obtained from 5% of poultry litter in pinewood have recorded higher heating value (28.81MJ/kg, at 500°C) than all the other ratios of poultry litter and this is due the high ash content of poultry litter (as the proportion of P.L increases, the ash content in the biomass increases which results in poor heating value). In addition, ANOVA analysis also depicts that the heating value and ash content of all the biochar obtained from different additive ratios had shown a significant change with respect to increase in the quantity of poultry litter in pinewood. However, ash content of biochar increases while increasing the weight ratio of the additive in the primary biomass and this was due to the high ash content contained in the poultry litter biomass when compared to the ash contained in pinewood. Further, from ANOVA analysis, the values of moisture content of biochar contained in different additive ratios were significant with respect to the amount of poultry litter in pinewood.

7.2.4 CONCLUSIONS

This section comprises of all the significant observations recorded while performing the experiments involved in this objective. In addition, it also reviews the key objective of this section and the effects of selected operating parameters in order to meet the same. From this objective, it was noticed that bio-oil yield was not affected at lower quantities of poultry litter in pinewood; however, significant changes were observed at higher ratios of poultry litter.

Eventually, the pH value of the bio-oil increases while increasing the ratio of poultry litter with pinewood. As a result, the pH value of bio-oil raised by 6% (at 15% of P.L in P.W) and thus meeting the objective of this project. Further, TAN value also confirms that the acidity of bio-oil decreases with increase in the composition of additive increases in primary biomass. In addition, density and heating value of both bio-oil and biochar decrease with increase in poultry litter and water content increase while increasing the ratio of poultry litter in pinewood. All the properties of bio-oil obtained from various additive ratios met the ASTM standards except the ash content, which requires further study (by altering the design of the auger reactor).

7.3 PRODUCTION OF BIO-OIL USING CASCADE PYROLYSIS REACTORS

This portion of the project can be referred as the second step in improvising the pH value of bio-oil and here, cascade pyrolysis reactors were used to meet the requirement. Cascade reactor is nothing but 2-stage reactor which is usually operated at two different temperatures. In this section, basic literature on biomass used, supporting thoughts for using cascade reactors, ideas followed and their consequences were detailed below.

7.3.1 SUMMARY

Fast pyrolysis is a thermo-chemical process, where different kinds of biomass are converted to liquid fuel called bio-oil. This process has attracted a lot of interest from industry and academia due to its high bio-oil yield. Though bio-oils are used in numerous applications, its (bio-oil) negative attributes limits the use of this form of bio-energy. Further acidity was considered as the main drawback (in this project) which pulls down the usage of bio-oils in various fields. Hence, in this objective, cheap and simple steps were followed to improvise the pH value of bio-oil. Here, pinewood was used as the feedstock for bio-oil production and two operating temperatures (300 and 500°C) were involved in producing high pH value bio-oil.

Physical properties of bio-oil such as pH, density, higher heating value, ash, water and solid content were analyzed and compared with the ASTM standard to document the effect of pyrolysis temperature. All the properties analyzed in this study of the bio-oil produced from 500°C met the specifications suggested by the ASTM standard except for the ash content. In addition, dynamic viscosity of bio-oil, physical properties of biochar were also measured and analyzed.

7.3.2 INTRODUCTION

Since 1990, interest in producing different forms of energy (including fuels) from bio-based products has gone high and the availability of biomass is abundant in US. From literature review, we know that, U.S. has the capacity to produce 368 million dry tons of forest residues annually and further, Alabama State has a potential to produce 2.81 million dry tons of forest residues, 64 million dry tons/year of logging and other residues, 6.45 million dry tons of primary mill residues, 63 thousand dry tons of secondary mill residues and 532 thousand dry tons of urban wood residues annually [5]. As the availability of the woody biomass is huge in the southern parts of US, especially in Alabama, pine wood was selected for this study.

Generally, biomass is made up of three basic constituents such as cellulose, hemi-cellulose and lignin. These constituents vary in their proportions for each type of biomass. Basically, cellulose provides strength to the wood, and it comprises of 40-50 wt % in dry wood, hemicellulose is also called as polyose, and it is 25-35 wt % and lignin holds 23-33% in softwood and 16-25% in hardwood [14]. Several studies have mentioned that hemicellulose decomposes rapidly when compared to cellulose and lignin [14, 82-83]. Usually, hemicellulose decomposes at temperature around 200-260°C [14, 84-85]. However, some studies reported that hemicellulose decomposes between 220-315°C, as shown in the Figure 30 [86-87].

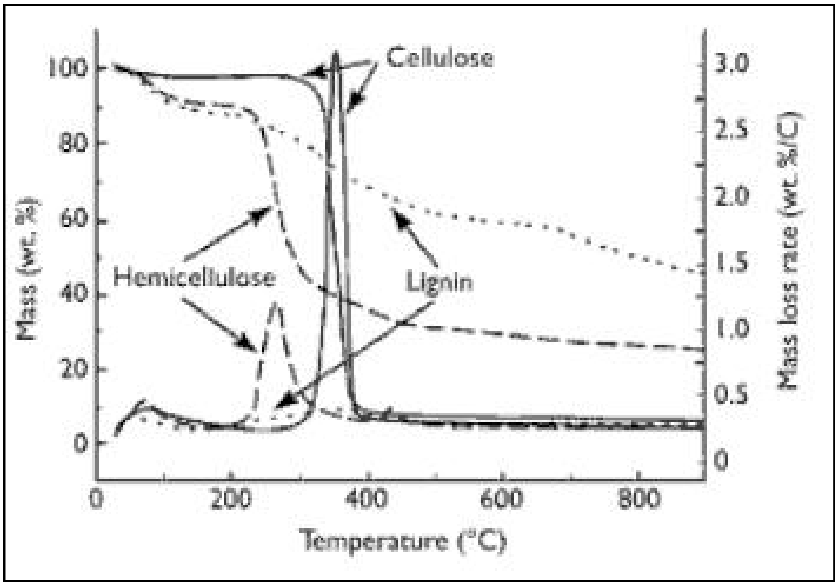

Figure 30: Thermo-gravimetric analysis of different constituents of biomass [86]

Further, hemicellulose is lower molecular weight compounds when compared to cellulose and it contains arabinose, galactose, mannose and xylose (which turns into furfural during dehydration) [14, 82, 88-89]. Tiwari and Ghosal (2005) reported that while comparing cellulose and hemicellulose, the later gives rise to more gas, less tar and less char in which the tar contains various organic compounds such as acetic acid, formic acid and other derivatives [85]. During fast pyrolysis, these compounds are collected in the form of acids in the bio-oil, thus increasing its acidic value.

In this objective, the biomass (pinewood) was first fast pyrolysed at 300°C (in order to remove the hemicellulose) and the char obtained from that reaction were again processed at 500°C so that most of the acid contents were removed in the first stage thereby, producing bio-oil with high pH value in the second stage. Hence, three iterations for each temperature were performed and the bio-oils obtained from those iterations were further analyzed to comprehend the influence of operating temperature over their (bio-oil) physical properties. In addition, different physical properties of biochar (left behind in the reactor) were also measured, and the methods involved in producing and analyzing both bio-oil and biochar were already elaborated in Chapter 5.

7.3.3 RESULTS AND DISCUSSIONS

In this section, the products (bio-oil, char and gases) obtained while processing pinewood at two different temperatures (300 and 500^oC) were reported. In addition, different physical properties of bio-oil (including viscosity) and biochar were also discussed.

A. EFFECT OF TEMPERATURE ON PRODUCT YIELD

From the first objective, we confirm that pinewood can produce high yield of bio-oil when compared to other biomass types involved in this work, and the maximum production of bio-oil was made at 500^oC. Hence, in this objective, pinewood and 500^oC (operating temperature for second stage) were selected as the operating parameters. Similar to previous objectives, biomass was processed thrice at each temperature to comprehend their behavior statistically. Figure 31 (refer Appendix D.1) shown below represents the yield of bio-oil, biochar and gases obtained from different operating temperatures of pinewood and the values shown in the figure were the average yield of different products obtained from three iterations.

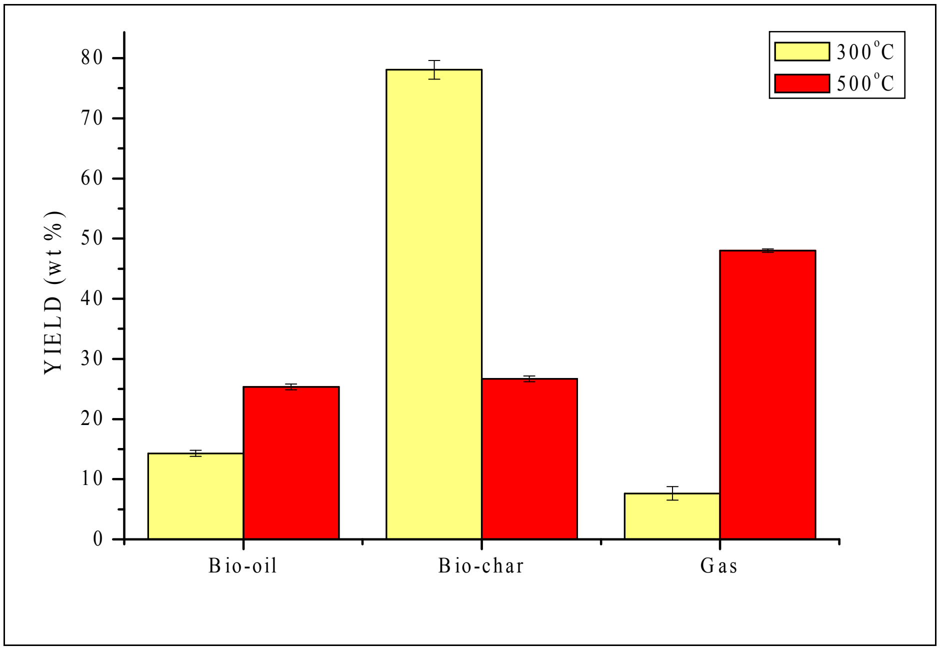

Figure 31: Product yield of pinewood at different operating temperatures

Here, X-axis of the graph represents the various products of the process and the Y-axis represents the yield (in wt %) of various products. As specified in the graph, yellow and red bars represent the operating temperature of the process.

Table 17: P values of the various products of pinewood at different temperatures

Operating temperatures	**P value of the products**		
	Bio-oil	**char**	**Gas**
Pinewood at 300 and 500°C	<0.0001	<0.0001	<0.0001

From Table 17 (refer Appendix D.1), it was evident that the yield of all the products of the process changes significantly with respect to operating temperature. Figure 31 reveals that at 300°C, nearly 15 wt% of bio-oil and more than 75 wt % of biochar were produced. Thereby we can say that, during this operating temperature (300 °C) most of the moisture contained in the biomass (pinewood, nearly 7 wt %) was transferred to bio-oil (liquid collected at this stage). Previous studies have also confirmed that removal of moisture occurs at 160 °C and over the temperature range 200-280 ^{o}C the hemicellulose present in the biomass decomposes and results in predominant yielding of volatile compounds into vapors [85]. Hence, it can be said that 15 wt% obtained from the first stage (at 300 ^{o}C) was none other than water and various sub-compounds of hemi-cellulose present in the biomass.

At the second stage of the process (500 ^{o}C), more than 25 wt% of bio-oil and 26 wt% of biochar were collected. However, the gas obtained from this stage was more than the other products (bio-oil and biochar). In all the biomass, combined weight ratio of cellulose and lignin are more than hemicellulose and generally, cellulose decomposes around 280 to 500 ^{o}C and lignin decomposes significantly above 320 ^{o}C [85]. Hence, the bio-oil contained in this stage (at 500 ^{o}C) has more materials derived from cellulose and lignin rather than hemicellulose (as most of it was removed in the first stage). Similar to the first objective, while increasing the operating temperature decrease in char and increase in gas production was observed here.

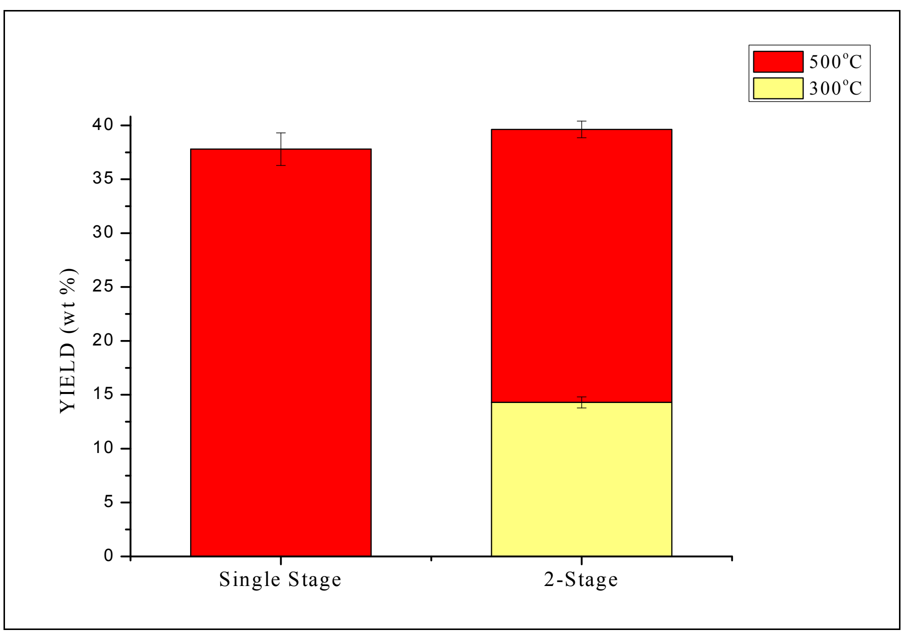

Figure 32: Comparison of bio-oil yield obtained from single stage and 2-stage process

Figure 32 (refer Appendix D.1) represents the comparison of bio-oil yield obtained from single and 2-stage process. Here, X-axis represents the different stages and Y-axis represents the yield (in wt %) of bio-oil. As specified in the graph, yellow and red bars represent the operating temperature of the process. However, 2-stage process produces more amount of bio-oil when compared to the single stage, statistically; there was no significant change in bio-oil yield.

B. EFFECT OF TEMPERATURE ON PHYSICAL PROPERTIES OF BIO-OIL

This section details all the physical properties of the bio-oil (from pinewood) produced at two different stages of the process. In addition, the physical properties of pinewood bio-oil obtained at single stage process (from first objective) were also compiled here (in order to understand the effect of stage process on the physical properties of bio-oil). Different physical properties (such as density, pH, calorific value, water content, solid content and ash content) of the pinewood bio-oil (obtained from stage process) were measured to characterize the bio-oil produced at different operating temperatures, and the values of those properties were summarized in the Table 18 (refer Appendix D.2) as shown below.

Table 18 consists of different physical properties of bio-oil obtained from processing pinewood biomass at different temperature along with ASTM standard D 7544-09 [61] of bio-oil (in order to compare the results obtained from the analysis). In addition, average and standard deviation of the experiments were calculated and ANOVA test (at 95% confidence interval) was performed between single stage and 2-stage process in order to understand their effect on different physical properties of bio-oil.

Table 18: Physical properties of pinewood bio-oil produced at different temperatures†.

Properties	Pine Wood (single stage, at 500°C)	Pyrolysis Temperature (°C)		p-value from ANOVA Test	ASTM Standard D 7544-09
		300	500		
Density, kg/m^3	1131 ± 21	1100 ± 16	1133 ± 6	0.8106	1100-1300
pH	3.73 ± 0.03	3.35 ± 0.07	3.82 ± 0.07	0.0019	Report
Water, wt%	17.23 ± 1.29	38.57 ± 1.67	14.35 ± 1.54	<0.0001	30 max.
HHV, MJ/kg	22.02 ± 0.51	X	20.27 ± 0.46	<0.0001	15 min.
Ash, wt%	0.33 ± 0.11	1.113 ± 0.21	0.625 ± 0.2	0.0014	0.25
Solid, wt%	0.59 ± 0.25	0.08 ± 0.01	1.37 ± 0.18	<0.0001	2.5 max.

† Values are means of nine repeated analysis and the numbers after ± is standard deviation and the symbol "X" represents below detection limit.

From the above table, it was obvious that operating temperature plays a significant role in the values of all the physical properties measured in this work. Further, the density of bio-oil obtained from 2-stage process (at 500 °C) was almost same as the density of bio-oil obtained from the single stage process. Simultaneously, ANOVA analysis also confirms that there was no significant change in the density of bio-oil obtained from single stage and 2-stage process. Certainly, the pH value of the bio-oil obtained from the 2-stage process (at 500 °C) was higher than the pH value of bio-oil obtained from a single stage process. Convincingly, statistical analysis also confirms the significant change in the pH value of bio-oil between single stage and 2-stage process.

As mention before, during the first stage (in 2-stage process), most of the moisture contained in the biomass was removed which corresponds to high water content, low solid content and poor heating value of bio-oil (below detection limit) at 300 ^{o}C. Hence the water content of the bio-oil obtained from the second stage was much lower than the first stage. Further, its values were less than the bio-oil obtained from processing pinewood in single stage process. Consecutively, ANOVA analysis also confirms that single stage and 2-stage process have a significant effect on heating value, water, ash, and solid content of bio-oil.

Apparently, the ash content of the bio-oil obtained in the 2-stage process was high when compared to the single stage process, which was quite unusual in this study. During the second stage of the 2-stage process, char obtained from the first stage were processed again and as the process progresses breaking of char particles take place. These tiny char particles produced during the second stage were carried away by the fumes and gases produced by the process and they settled in the bio-oil (during condensation), hence high solid content of bio-oil was noticed in the second stage. However, it (tiny char in bio-oil) did not reflect in the heating value of the bio-oil obtained at 500 ^{o}C, as it measured less than the heating value of bio-oil obtained from the single stage which was also not expected in this study.

C. VISCOSITY ANALYSIS OF PINEWOOD BIO-OIL

Kinematic viscosity plays a significant role in design, handling and transportation of the equipment (for bio-oil). Here, the viscosity analysis on bio-oils obtained from pinewood at different temperatures was carried out at 40°C and their results were shown in the Figure 33 (refer Appendix D.3).

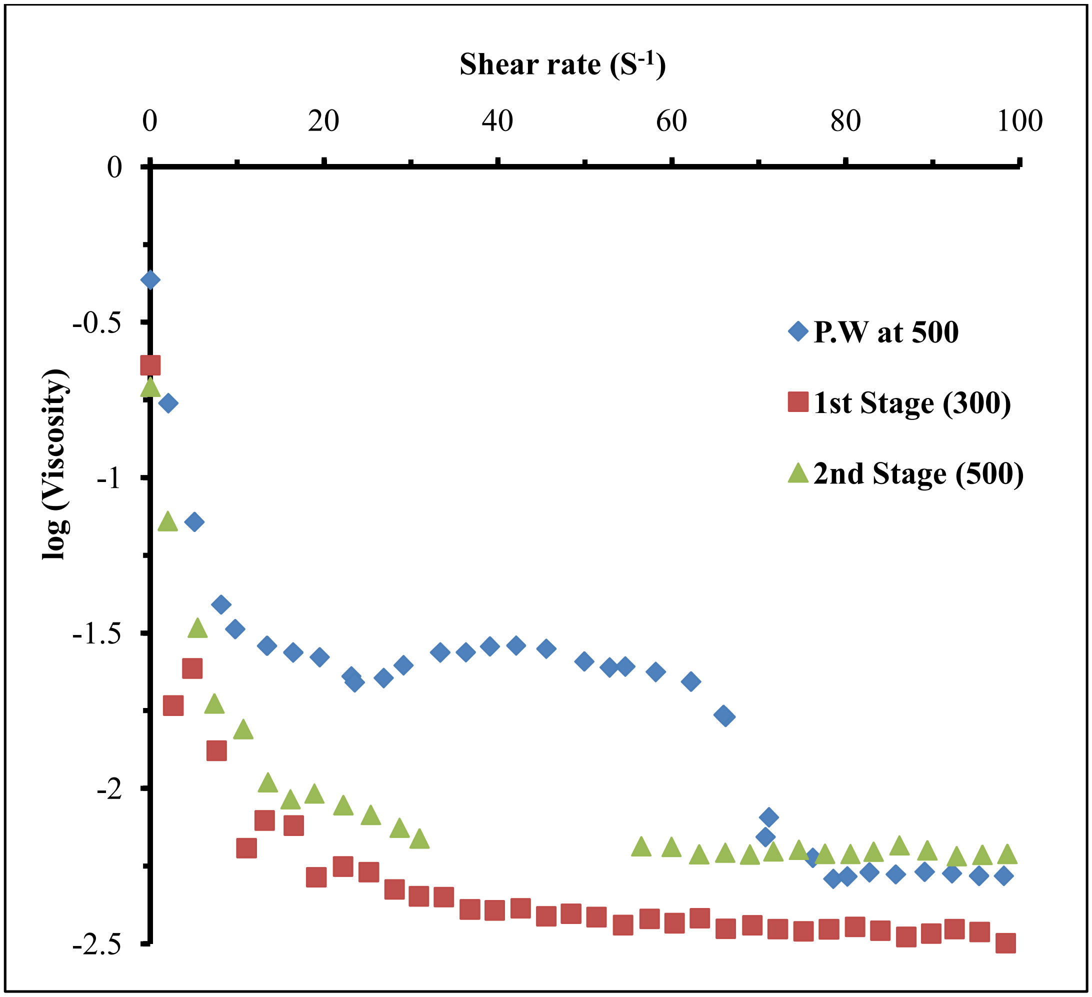

Figure 33: Viscosity analysis on pinewood bio-oil at different operating temperatures

Figure 33 shows the variation in log (viscosity) (as the shear rate was increased from 0.1 to 100 s^{-1}) for different types of bio-oil obtained from different stages of the process. In addition, the dynamic viscosity of bio-oil obtained from single stage process (using pinewood biomass) was also incorporated in this figure. Previous studies have also stated that at higher shear rate, viscosity of bio-oil produced from different operating temperatures behaves in a similar manner (with respect to values of viscosity) [23, 56, 68]. From the above figure, it was evident that viscosity of bio-oil obtained from 2-stage process was less than the bio-oil obtained from single stage process. Further, viscosity of bio-oil obtained from first stage was less than the viscosity of bio-oil obtained from second stage and this is due to presence of high water content present in the bio-oil (obtained from the first stage of the process).

D. EFFECT OF TEMPERATURE ON BIOCHAR

In this objective, two different operating temperatures were used (300 and 500°C) which correspond to the production of two different types of biochar. Basically, this section comprises of, the effect of temperature on different physical properties of biochar obtained from processing pinewood. In addition, ANOVA analysis at 95% confidence interval was also carried out (between single stage and 2-stage process) on the various properties of bio-char. Table 19 (refer Appendix D.4) shows the characterization of bio-char (pinewood) obtained from different operating temperatures.

Table 19: Physical properties of biochar produced from different temperatures†

Properties	**Pine Wood (Single stage, at 500°C)**	**Pyrolysis Temperatures (°C)**		**p-value from ANOVA Test**
		300	**500**	
HHV, MJ/kg	30.45 ± 0.36	21 ± 0.052	31.73 ± 0.2	<0.0001
Ash, wt%	0.51 ± 0.22	0.36 ± 0.04	2.14 ± 0.26	<0.0001
Moisture content, wt%	3.64 ± 0.25	2.98 ± 0.34	1.87 ± 0.52	<0.0001

† Values are means of nine repeated analysis and the numbers after ± is standard deviation.

From Table19, statistically it was clear that all the physical properties of the biochar changes significantly with the type of process. Several studies also confirm that as the operating temperature of the process increases, the heating value of the biochar also increases [23]. Similarly, in this work, the heating value of biochar obtained at 500°C was higher than the heating value of the biochar obtained at 300°C. Further, the heating value of biochar obtained from the 2-stage process was higher than the biochar obtained from the single stage process and this was due to repetitive heating (biochar obtained from the first stage was heated again in the second stage).

Ash content of the biochar obtained from 300°C (0.36 wt %) was very close to the ash content present in the pinewood biomass (0.3 wt %). However, ash content of the biochar at 500°C was very high and the reason behind this is mysterious. Apparently the moisture content of the biochar used in the second stage (of the 2-stage process) was less than the first stage because during the first stage, more water was removed from the biomass, and leaving less amount of moisture in the biochar.

7.3.4 CONCLUSIONS

This section includes all the significant conclusions made while performing various stages of this objective. In addition, it also reviews the key objective of this section and effects of the operating parameters selected in order to meet the prime objective (producing bio-oil of high pH value) were also discussed here. From the results obtained from this objective, it was evident that pH value of the bio-oil acquired from the 2-stage process was higher than the single stage process (raised by 3%) and thus meeting the objective (producing bio-oil of high pH value) of this work. However, 25 wt % of bio-oil was produced at the second stage of the process. By the end of the reaction, this process leads to high biochar production. Heating value of biochar obtained from the second stage (cascade) of this process records higher values when compared to the single stage process. Further, there was no significant change in the total energy contained in the different products (bio-oil and bio-char) of the process obtained from single stage (52.47 MJ/kg) and 2-stage (52 MJ/kg) methods. Here, moisture content of the biomass was removed in the first stage and hence producing bio-oil with less water content in the second stage.

Nevertheless, the heating value of the bio-oil obtained from the two stage process was lower than the single stage process.

CHAPTER 8

CONCLUSIONS & RECOMENTATIONS

This section summarizes the major results, conclusions and discussions made during various stages of this project. The key objective of this work along with the experience gained while performing fast pyrolysis process under different operating conditions were specified below. Basically, different feedstocks such as pinewood, underutilized forest biomass, poultry litter and various proportions of biomass mixture (pinewood and poultry litter) were investigated at different temperature in between 425 to 500°C. Detailed reviews on various objectives of this work were also detailed here. In addition, recommendations for improvising the instrument (from performance, life and maintenance point of view) and increasing the bio-oil production were also given below.

8.1 CONCLUSIONS

The main objective of this project was to produce bio-oil with high pH value using cheap and simple methods so that the bio-oil can be used at least in the existing refineries without or less upgrading. Hence in the first objective, fast pyrolysis of selected feedstocks were performed at selected temperatures in between 425 to 500°C in an auger reactor. Pinewood manages to produce maximum bio-oil yield (at 500°C) than underutilized forest biomass and poultry litter. Different physical properties of all the bio-oils (obtained from different biomass at different operating temperatures) were measured and analyzed. From the analysis, it was evident that the pH value of poultry litter was high (basic property, 9.4) when compared to the bio-oil obtained from the woody biomass (P.W-3.7 and U.U-3.1). Hence, pinewood and poultry litter were selected as the primary and secondary biomass for the second objective and 500°C was selected as the operating temperature (as high yield of bio-oil was obtained while processing pinewood).

Second objective of this work was considered as the first step in improving the pH value of the bio-oil. Here, poultry litter was considered as an additive and it was mixed with pinewood (primary biomass) at 5, 10 and 15 wt %, later these mixture are operated at 500°C. The physical properties of bio-oil obtained from three different ratios of poultry litter (with pinewood) were measured and compared with ASTM standard. The bio-oil produced at 15% wt ratio of poultry litter showed high values of pH when compared to the bio-oil obtained from processing pure pinewood biomass, thus meeting the objective of the project. Further, TAN value also confirms that as the composition of poultry litter increases in pine wood, the acidity of bio-oil decreases significantly. Heating value of bio-oil decreases while increasing the amount of poultry litter in pinewood. The bio-oil produced at different weight ratios of poultry litter (with pinewood) met the specifications of the measured properties. However, the ash content of the bio-oil failed to met the same. It was also observed that, further adding of poultry litter in pinewood would result in producing bio-oil with poor physical properties.

Another direction in achieving high pH value of bio-oil was detailed in the third objective of this work. In this technique, biomass (pinewood) was processed at two different temperatures in which the hemicellulose and water were removed in the first stage and quality bio-oil was collected in the later. The physical properties of bio-oil produced at two different stages were measured and compared with the bio-oil obtained from the single stage and with the ASTM standards. The bio-oil obtained from 2-stage process met the standards except ash content. The pH value of the bio-oil obtained from the 2-stage process was high when compared to the single stage process, and thus satisfying the requirement of this project.

Certainly, viscosity analysis showed that at higher shear rates, bio-oils produced from pinewood and underutilized biomass behaves like a Newtonian fluid. However, the bio-oil obtained from poultry litter appeared as a pseudo plastic fluid (even at higher shear rates). The results obtained from the second and third objectives conclude that both the techniques worked good in producing high pH value bio-oil. Nevertheless, the ash content of the bio-oil obtained from pinewood and underutilized biomass required further study.

8.2 RECOMENDATIONS

Recommendations mentioned in this section are the future work that can be done on the auger reactor in order to improvise its efficiency. Basically, it helps in increasing the bio-oil production, reducing the leaking, easy operation and maintenance (through design modification).

Primarily, bio-oil yield can be raised by placing the condenser #1 in a cooling bath/tub (<1°C). Generally, under current design, fumes produced during this process were passed through the condenser operated at room temperature, and by operating this equipment (condenser #1) at lower temperature results in high bio-oil production (because of larger temperature difference). In addition, bio-oil production shall be increased by using additional condensers or by modifying the design of the condenser #2 so that condensation time (time taken by the fumes to pass through the heat exchangers) can be increased and thus increasing the yield of bio-oil. Further, bio-oil yield can be raised slightly by reducing the leakage of fumes during the process.

Leakage of fumes (at bottom reactor) is another major drawback of the system because, sometimes, it is difficult for the operator to run the machine. This can be controlled/ reduced by mounting the transmission system of the reactor towards the other side of char collector. Certainly, clogging of char (at char collector) is another problem faced while operating the reactor and this can be reduced by increasing/altering the cross-section area (rectangular cross-section instead of circular) of the char collector. Further, this design (rectangular cross-section) helps in easy removal of char from the reactor and eventually resulting in better quality of bio-oil (with less char and ash content).

Apart from this, current design of hopper shall be changed to a cylindrical structure for easy and free flow of biomass into the top auger. High torque motors (for uniform speed of augers), orifice meters (to determine the flow rate of carrying gas) and thermocouples (to measure the temperature of the biomass inside the reactor) shall be added to the current system in order to understand the process in a better way.

From the research point of view, theoretically, ash content of biochar increases at higher operating temperatures. However, there was no increasing trend in ash content was noticed while increasing the operating temperature. Hence, it requires further study. Apart from this, reason behind high water content in poultry litter bio-oil obtained at 425°C is to be analyzed. Basically, while comparing the ash and solid content of pinewood and poultry litter bio-oils (from 100 wt% pure biomass), pinewood bio-oil has more amount of ash and solid particles when compared to poultry litter bio-oil. Eventually, while increasing the composition of poultry litter in pinewood should reduce the ash and solid contents of the bio-oil (obtained from the biomass mixture). However, the trend was not noticed from this study and it requires further analysis.

In addition, bio-oil obtained from 2-stage pyrolysis process requires further analysis to find out why the pH value did not increase significantly even after removing hemicellulose from 1-stage. Apart from this, ash content of biochar requires further study because of the amount of ash contained in the 2-stage process was very high than theoretical values.

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APPENDIX A

SUPPLEMENTARY DATA FOR BIOMASS CHARECTERIZATION

All the row data used for the Table 6 are reported in this Appendix. Data tables shown below represent the type of biomass and their physical properties recorded during the characterization of different biomass involved in this work.

A.1 PHYSICAL PROPERTIES OF PINE WOOD BIOMASS

Table A.1.1. Data for density of pine wood biomass.

S. No.	Weight of the beaker	Weight of the Beaker with biomass	Weight of the biomass	Density (g/cc)
1	5.7221	6.3607	0.6386	0.3193
2	5.7245	6.3676	0.6431	0.3215
3	5.7720	6.4180	0.6460	0.3230
			Average	0.32

Density calculations:

Weight of the biomass (g) = Weight of the Beaker with biomass - Weight of the beaker

$$\text{Density (g/cc)} = \frac{\text{Weight of the biomass}}{\text{Volume of the beaker (100ml)}}$$

Table A.1.2. Data for moisture content of pine wood biomass.

S. No.	Weight of the crucible	Weight of the crucible with biomass	Weight of the biomass	Weight of the crucible with biomass after drying	Weight of the biomass after drying	Weight Difference	Moisture (%)
1	47.8796	52.2513	4.3717	51.9363	4.0567	0.3150	7.2054
2	48.1250	50.1267	2.0017	49.9728	1.8478	0.1539	7.6885
3	48.6719	51.6717	2.9998	51.4428	2.7709	0.2289	7.6305
						Average	7.51

Moisture content calculations:

Weight of the biomass (g) = Weight of the crucible with biomass - Weight of the crucible

Weight of the biomass after drying (g) = Weight of the crucible with biomass after drying - Weight of the crucible

Weight Difference (g) = Weight of the biomass - Weight of the biomass after drying

$$\text{Moisture (\%)} = \frac{\text{Weight Difference x 100 \%}}{\text{Weight of the biomass}}$$

Table A.1.3. Data for ash content of pine wood biomass

S. No.	Weight of the crucible	Weight of the crucible with biomass	Weight of the biomass	Weight of the crucible with biomass after drying	Weight of the biomass after test	Weight of ash	Ash content (%)
1	18.6988	18.6975	20.537	1.8395	18.7031	0.0056	0.3044
2	16.9612	16.9608	18.4771	1.5163	16.9642	0.0034	0.2242
3	19.2093	19.2074	21.2176	2.0102	19.2154	0.0082	0.3979
						Average	0.31

Ash content calculations:

Weight of the biomass (g) = Weight of the crucible with biomass - Weight of the crucible

Weight of the biomass after test (g) = Weight of the crucible with biomass after drying – Weight of the crucible

Weight of ash (g) = Weight of the biomass - Weight of the biomass after test

$$\text{Ash Content (\%)} = \frac{\text{Weight of ash x 100 \%}}{\text{Weight of the biomass}}$$

Table A.1.4. Data for higher heating value of pine wood biomass

S. No.	Wt. of the biomass	Higher heating value (MJ/kg)
1	0.51	18.691
2	0.4672	18.618
3	0.5672	18.665
	Average	18.66

A.2 PHYSICAL PROPERTIES OF UNDERUTILIZED FOREST BIOMASS

Table A.2.1. Data for density of underutilized forest biomass.

S. No.	Weight of the beaker	Weight of the Beaker with biomass	Weight of the biomass	Density (g/cc)
1	5.7224	6.2542	0.5318	0.2659
2	5.7225	6.2449	0.5224	0.2612
3	5.7226	6.2444	0.5218	0.2609
			Average	0.26

Table A.2.2. Data for moisture content of underutilized forest biomass.

S. No.	Weight of the crucible	Weight of the crucible with biomass	Weight of the biomass	Weight of the crucible with biomass after drying	Weight of the biomass after drying	Weight Difference	Moisture (%)
1	17.759	19.493	1.734	19.405	1.646	0.088	5.0749
2	17.343	19.117	1.774	19.025	1.682	0.092	5.1860
3	17.418	19.449	2.031	19.354	1.936	0.095	4.6774
						Average	4.98

Table A.2.3. Data for ash content of underutilized forest biomass

S. No.	Weight of the crucible	Weight of the crucible with biomass	Weight of the biomass	Weight of the crucible with biomass after drying	Weight of the biomass after test	Weight of ash	Ash content (%)
1	18.1371	18.1365	19.2831	0.9066	18.1450	0.0085	0.9375
2	17.9550	17.9550	19.0025	1.0475	17.9635	0.0085	0.8114
3	17.8273	17.8264	18.7463	0.9199	17.8348	0.0084	0.9131
						Average	0.89

Table A.2.4. Data for higher heating value of underutilized forest biomass

S. No.	Wt. of the biomass	Higher heating value (MJ/kg)
1	0.5023	18.093
2	0.5126	17.989
3	0.5509	18.122
	Average	18.07

A.3 PHYSICAL PROPERTIES OF POULTRY LITTER BIOMASS

Table A.3.1 Data for density of poultry litter biomass.

S. No.	Weight of the beaker	Weight of the Beaker with biomass	Weight of the biomass	Density (g/cc)
1	5.7228	6.7607	1.0379	0.5190
2	5.7235	6.7674	1.0439	0.5220
3	5.7229	6.7591	1.0362	0.5181
			Average	0.52

Table A.3.2. Data for moisture content of poultry litter biomass.

S. No.	Weight of the crucible	Weight of the crucible with biomass	Weight of the biomass	Weight of the crucible with biomass after drying	Weight of the biomass after drying	Weight Difference	Moisture (%)
1	46.5235	59.0948	12.5713	57.4907	10.9672	1.6041	12.7600
2	48.144	61.4785	13.3345	59.7782	11.6342	1.7003	12.7511
3	48.7824	62.0893	13.3069	60.3901	11.6077	1.6992	12.7693
						Average	7.76

Table A.3.3. Data for ash content of poultry litter biomass

S. No.	Weight of the crucible	Weight of the crucible with biomass	Weight of the biomass	Weight of the crucible with biomass after drying	Weight of the biomass after test	Weight of ash	Ash content (%)
1	16.9228	16.9228	22.4197	5.4969	18.8371	1.9143	34.8250
2	18.9612	18.9604	22.5412	3.5808	20.2095	1.2491	34.8832
3	17.7841	17.7838	21.4985	3.7147	19.0595	1.2757	34.3419
						Average	34.68

Table A.3.4. Data for higher heating value of poultry litter biomass

S. No.	Wt. of the biomass	Higher heating value (MJ/kg)
1	0.5012	9.664
2	0.4995	9.677
3	0.5109	9.65
	Average	9.66

APPENDIX B

SUPPLEMENTARY DATA FOR SELECTED FIGURES AND TABLES INVOLVED IN PRODUCTION OF BIO-OIL FROM SELECTED BIOMASS

This appendix comprises of all the data, SAS code and SAS results involved in constructing the figures (Figure 24-27) and tables (Table7-13) of the first specific objective of this work. Data tables shown below represents the yield of bio-oil, char and gas and their physical properties, obtained while operating the respective biomass at different temperatures.

B.1 EFFECT OF TEMPERATURE ON PRODUCT YIELD

Table B.1.1. Data for yield of bio-oil obtained from selected biomass at different temperatures (refer Figure 24).

Operating temperature (°C)	Iteration No.	Bio-oil from selected biomass (wt. %)		
		P.W.	U.U	P.L.
425	1	30	30.4	32.2
	2	29.6	29.6	32.8
	3	29	31.2	33
450	1	30	31.8	33.4
	2	32.2	35	33.6
	3	33.4	30.8	32.8
475	1	36.2	32	35.4
	2	34.6	32	34.4
	3	35.8	31.2	34.6
500	1	37.6	34.2	31.2
	2	36.4	32.8	29.4
	3	39.4	31.4	26

SAS code for pine wood bio-oil (refer Table 7):

```
data OILYIELD;
input temp yield;
datalines;
425    30
425    29.6
425    29
450    30
450    32.2
450    33.4
475    36.2
475    34.6
475    35.8
500    37.6
500    36.4
500    39.4
;
run;
proc anova data=OILYIELD;
class temp;
model yield=temp;
means temp/ alpha=0.05;
run;
```

SAS results for pine wood bio-oil:

```
                        The ANOVA Procedure
              Level of          ------------yield-----------
              temp         N             Mean          Std Dev

              425          3       29.5333333       0.50332230
              450          3       31.8666667       1.72433562
              475          3       35.5333333       0.83266640
              500          3       37.8000000       1.50996689

Dependent Variable: yield
                                         Sum of
      Source                    DF          Squares     Mean Square    F Value    Pr > F

      Model                      3      122.6766667      40.8922222      26.38    0.0002

      Error                      8       12.4000000       1.5500000

      Corrected Total           11      135.0766667

                   R-Square     Coeff Var      Root MSE    yield Mean
                   0.908200      3.696160      1.244990      33.68333

      Source                    DF         Anova SS     Mean Square    F Value    Pr > F
      temp                       3      122.6766667      40.8922222      26.38    0.0002
```

SAS code for underutilized forest bio-oil (refer Table 7):

```
data OILYIELD;
input temp yield;
```

```
datalines;
425    30.4
425    29.6
425    31.2
450    31.8
450    35
450    30.8
475    32
475    32
475    31.2
500    34.2
500    32.8
500    31.4
;
run;
proc anova data=OILYIELD;
class temp;
model yield=temp;
means temp/ alpha=0.05;
run;
```

SAS result for underutilized forest bio-oil:

```
                          The ANOVA Procedure

                Level of           ------------yield------------
                temp         N             Mean          Std Dev

                425          3       30.4000000       0.80000000
                450          3       32.5333333       2.19393102
                475          3       31.7333333       0.46188022
                500          3       32.8000000       1.40000000

Dependent Variable: yield

                                        Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        3     10.45333333      3.48444444       1.83    0.2202

      Error                        8     15.25333333      1.90666667

      Corrected Total             11     25.70666667


               R-Square     Coeff Var      Root MSE    yield Mean

               0.406639      4.333120      1.380821      31.86667


      Source                      DF        Anova SS     Mean Square    F Value    Pr > F

      temp                         3     10.45333333      3.48444444       1.83    0.2202
```

SAS code for poultry litter bio-oil (refer Table 7):

```
data OILYIELD;
input temp yield;
datalines;
425    32.2
425    32.8
425    33
450    33.4
450    33.6
450    32.8
475    35.4
475    34.4
475    34.6
500    31.2
500    29.4
500    26
;
run;
proc anova data=OILYIELD;
class temp;
model yield=temp;
means temp/ alpha=0.05;
run;
```

SAS result for poultry litter bio-oil:

```
                              The ANOVA Procedure

                    Level of            ------------yield------------
                    temp         N             Mean          Std Dev

                    425          3       32.6666667       0.41633320
                    450          3       33.2666667       0.41633320
                    475          3       34.8000000       0.52915026
                    500          3       28.8666667       2.64070698

Dependent Variable: yield

                                        Sum of
      Source                      DF      Squares     Mean Square    F Value    Pr > F

      Model                        3   57.20000000    19.06666667      10.04    0.0044

      Error                        8   15.20000000     1.90000000

      Corrected Total             11   72.40000000


                   R-Square     Coeff Var      Root MSE    yield Mean

                   0.790055      4.254336      1.378405      32.40000

      Source                      DF      Anova SS    Mean Square    F Value    Pr > F

      temp                         3   57.20000000    19.06666667      10.04    0.0044
```

Table B.1.2. Data for yield of bio-char obtained from selected biomass at different temperatures (refer Figure 25).

Operating temperature (°C)	Iteration No.	Bio-char from selected biomass (wt. %)		
		P.W.	U.U	P.L.
425	1	48.8	38.6	49.4
	2	49.6	48	48.4
	3	50.4	39.6	47.2
450	1	43	40.8	43
	2	37.8	36.4	42.6
	3	41.2	40.4	45.6
475	1	32.2	39	39.6
	2	34.2	40.4	40.8
	3	32.8	34.4	40.8
500	1	28.4	31	36
	2	23.6	30.2	38.4
	3	21	24	39.2

SAS code for pine wood bio-char:

```
data CHARYIELD;
input temp yield;
datalines;
425    48.8
425    49.6
425    50.4
450    43
450    37.8
450    41.2
475    32.2
475    34.2
475    32.8
500    28.4
500    23.6
500    21
;
run;
proc anova data=CHARYIELD;
class temp;
model yield=temp;
means temp/ alpha=0.05;
run;
```

SAS results for pine wood bio-char:

```
                          The ANOVA Procedure

              Level of          ------------yield-----------
              temp         N            Mean           Std Dev

              425          3      49.6000000        0.80000000
              450          3      40.6666667        2.64070698
              475          3      33.0666667        1.02632029
              500          3      24.3333333        3.75410886

Dependent Variable: yield

                                            Sum of
      Source                      DF        Squares     Mean Square    F Value    Pr > F

      Model                        3     1044.276667     348.092222      61.18    <.0001

      Error                        8       45.520000       5.690000

      Corrected Total             11     1089.796667


                  R-Square     Coeff Var      Root MSE     yield Mean

                  0.958231      6.461505      2.385372       36.91667


      Source                      DF        Anova SS    Mean Square    F Value    Pr > F

      temp                         3     1044.276667     348.092222      61.18    <.0001
```

SAS code for underutilized forest bio-char (refer Table 7):

```
data CHARYIELD;
input temp yield;
datalines;
425   38.6
425   48
425   39.6
450   44.8
450   36.4
450   40.4
475   39
475   40.4
475   34.4
500   31
500   30.2
500   24
;
run;
proc anova data=CHARYIELD;
class temp;
model yield=temp;
means temp/ alpha=0.05;
```

```
run;
```

SAS result for underutilized forest bio-char:

```
                              The ANOVA Procedure

                Level of          ------------yield------------
                temp          N             Mean          Std Dev

                425           3       42.0666667       5.16268664
                450           3       40.5333333       4.20158700
                475           3       37.9333333       3.13900196
                500           3       28.4000000       3.83144881

Dependent Variable: yield

                                            Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        3     338.3066667     112.7688889       6.55    0.0151

      Error                        8     137.6800000      17.2100000

      Corrected Total             11     475.9866667


               R-Square     Coeff Var      Root MSE    yield Mean

               0.710748      11.14188      4.148494      37.23333


      Source                      DF        Anova SS     Mean Square    F Value    Pr > F

      temp                         3     338.3066667     112.7688889       6.55    0.0151
```

SAS code for poultry litter bio-char (refer Table 7):

```
data CHARYIELD;
input temp yield;
datalines;
425   49.4
425   48.4
425   47.2
450   43
450   42.6
450   45.6
475   39.6
475   40.8
475   40.8
500   36
500   38.4
500   39.2
;
run;
proc anova data=CHARYIELD;
class temp;
```

```
model yield=temp;
means temp/ alpha=0.05;
run;
```

SAS result for poultry litter bio-char:

```
                                        The ANOVA Procedure

                         Level of          ------------yield------------
                         temp         N            Mean          Std Dev

                         425          3      48.3333333       1.10151411
                         450          3      43.7333333       1.62890556
                         475          3      40.4000000       0.69282032
                         500          3      37.8666667       1.66533280

Dependent Variable: yield

                                                Sum of
      Source                      DF           Squares     Mean Square    F Value    Pr > F

      Model                        3       184.1966667      61.3988889      34.49    <.0001

      Error                        8        14.2400000       1.7800000

      Corrected Total             11       198.4366667

                        R-Square     Coeff Var      Root MSE    yield Mean
                        0.928239      3.133072      1.334166      42.58333

      Source                      DF          Anova SS     Mean Square    F Value    Pr > F
      temp                         3       184.1966667      61.3988889      34.49    <.0001
```

Table B.1.3. Data for yield of bio-char obtained from selected biomass at different temperatures (refer Figure 26).

Operating temperature (°C)	Iteration No.	Gas from selected biomass (wt. %)		
		P.W.	U.U	P.L.
425	1	21.2	31	18.4
	2	20.8	22.4	18.8
	3	20.6	29.2	19.8
450	1	27	27.4	23.6
	2	30	28.6	23.8
	3	25.4	28.8	21.6
475	1	31.6	29	25
	2	31.2	27.6	24.8
	3	31.4	34.4	24.6
500	1	34	34.8	32.8
	2	40	37	32.2
	3	39.6	44.6	34.8

SAS code for pine wood gas (refer Table 7):

```
data GASYIELD;
input temp yield;
datalines;
425    21.2
425    20.8
425    20.6
450    27
450    30
450    25.4
475    31.6
475    31.2
475    31.4
500    34
500    40
500    39.6
;
run;
proc anova data=GASYIELD;
class temp;
model yield=temp;
means temp/ alpha=0.05;
run;
```

SAS results for pine wood gas:

The ANOVA Procedure

Level of temp	N	yield Mean	yield Std Dev
425	3	20.8666667	0.30550505
450	3	27.4666667	2.33523732
475	3	31.4000000	0.20000000
500	3	37.8666667	3.35459883

Dependent Variable: yield

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	456.7200000	152.2400000	36.16	<.0001
Error	8	33.6800000	4.2100000		
Corrected Total	11	490.4000000			

R-Square	Coeff Var	Root MSE	yield Mean
0.931321	6.979008	2.051828	29.40000

Source	DF	Anova SS	Mean Square	F Value	Pr > F

```
temp                         3      456.7200000      152.2400000      36.16    <.0001
```

SAS code for underutilized forest gas (refer Table 7):

```
data GASYIELD;
input temp yield;
datalines;
425    31
425    22.4
425    29.2
450    23.4
450    28.6
450    28.8
475    29
475    27.6
475    34.4
500    34.8
500    37
500    44.6
;
run;
proc anova data=GASYIELD;
class temp;
model yield=temp;
means temp/ alpha=0.05;
run;
```

SAS result for underutilized forest gas:

```
                                   The ANOVA Procedure

                        Level of           ------------yield------------
                        temp          N             Mean          Std Dev

                        425           3       27.5333333       4.53578365
                        450           3       26.9333333       3.06159000
                        475           3       30.3333333       3.59072880
                        500           3       38.8000000       5.14198405


Dependent Variable: yield

                                               Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F

      Model                        3      269.4000000      89.8000000       5.18    0.0279

      Error                        8      138.5600000      17.3200000

      Corrected Total             11      407.9600000


                       R-Square     Coeff Var      Root MSE    yield Mean

                       0.660359      13.46838      4.161730      30.90000
```

```
Source                      DF        Anova SS     Mean Square    F Value    Pr > F

temp                         3     269.4000000      89.8000000       5.18    0.0279
```

SAS code for poultry litter gas (refer Table 7):

```
data GASYIELD;
input temp yield;
datalines;
425    18.4
425    18.8
425    19.8
450    23.6
450    23.8
450    21.6
475    25
475    24.8
475    24.6
500    32.8
500    32.2
500    34.8
;
run;
proc anova data=GASYIELD;
class temp;
model yield=temp;
means temp/ alpha=0.05;
run;
```

SAS result for poultry litter gas:

```
                                      The ANOVA Procedure

                         Level of          ------------yield------------
                         temp          N            Mean          Std Dev

                         425           3      19.0000000       0.72111026
                         450           3      23.0000000       1.21655251
                         475           3      24.8000000       0.20000000
                         500           3      33.2666667       1.36137186

Dependent Variable: yield

                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F
      Model                        3     325.1300000     108.3766667     111.35    <.0001
      Error                        8       7.7866667       0.9733333
      Corrected Total             11     332.9166667
                        R-Square     Coeff Var      Root MSE     yield Mean
                        0.976611      3.943677      0.986577       25.01667

      Source                      DF        Anova SS     Mean Square    F Value    Pr > F
      temp                         3     325.1300000     108.3766667     111.35    <.0001
```

B.2 EFFECT OF TEMPERATURE ON PHYSICAL PROPERTIES OF BIO-OIL

Table B.2.1. Data for density of pine wood bio-oil (refer Table 8).

Temp (°C)	Iteration No.	Sample #1				Sample #2				Sample #3			
		Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)	Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)	Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)
425	1	5.7221	8.0354	2.3133	1156.65	5.7245	8.0341	2.3096	1154.8	5.7300	8.0457	2.3157	1157.85
	2	5.7245	8.0341	2.3096	1154.8	5.7372	8.0417	2.3045	1152.25	5.8418	8.1783	2.3365	1168.25
	3	5.7720	8.0613	2.2893	1144.65	5.7779	8.0595	2.2816	1140.8	5.7790	8.0674	2.2884	1144.2
450	1	5.7448	8.0155	2.2707	1135.35	5.7498	8.0448	2.2950	1147.5	5.7542	8.0267	2.2725	1136.25
	2	5.7426	8.0660	2.3234	1161.7	5.9782	8.3175	2.3393	1169.65	5.7589	8.0984	2.3395	1169.75
	3	5.7544	8.0445	2.2901	1145.05	5.9348	8.2192	2.2844	1142.2	5.7581	8.0431	2.2850	1142.5
475	1	5.7712	8.0048	2.2336	1116.8	5.8699	8.0737	2.2038	1101.9	5.7412	8.0121	2.2709	1135.45
	2	5.7490	8.0434	2.2944	1147.2	5.9588	8.2517	2.2929	1146.45	5.7763	8.0265	2.2502	1125.1
	3	5.7392	8.0000	2.2608	1130.4	5.7551	8.1157	2.3606	1180.3	5.7545	8.0054	2.2509	1125.45
500	1	5.7391	7.9807	2.2416	1120.8	5.8180	8.0104	2.1924	1096.2	5.7492	8.0101	2.2609	1130.45
	2	5.7511	8.0867	2.3356	1167.8	5.7514	8.0567	2.3053	1152.65	5.8874	8.1847	2.2973	1148.65
	3	5.7589	8.0115	2.2526	1126.3	5.7563	8.0100	2.2537	1126.85	5.7554	7.9898	2.2344	1117.2

Note: Column “Iteration No.” represents the number of iterations made on the particular temperature and the columns Sample #1, #2 and #3 represents the experiments made on each Iteration No. Here, the column “Temp” represents the operating temperature (°C) of the process.

SAS code for density of pine wood bio-oil:

```
data Pinewood;
input temp yield;
datalines;
425    1156.65
425    1154.8
425    1144.65
450    1135.35
450    1161.7
450    1145.05
475    1116.8
475    1147.2
475    1130.4
500    1120.8
500    1167.8
500    1126.3
425    1154.8
425    1152.25
425    1140.8
450    1147.5
450    1169.65
450    1142.2
475    1101.9
475    1146.45
475    1180.3
500    1096.2
500    1152.65
500    1126.85
425    1157.85
425    1168.25
425    1144.2
450    1136.25
450    1169.75
450    1142.5
475    1135.45
475    1125.1
475    1125.45
500    1130.45
500    1148.65
500    1117.2
;
run;
proc anova data=Pinewood;
class temp;
model yield=temp;
means temp/ alpha=0.05;
run;
```

SAS result for density of pine wood bio-oil:

```
                  The ANOVA Procedure

         Level of          ------------yield------------
         temp         N              Mean           Std Dev
```

```
        425          9        1152.69444        8.4529006
        450          9        1149.99444       13.5305313
        475          9        1134.33889       22.2641076
        500          9        1131.87778       21.4262851

Dependent Variable: yield

                                            Sum of
      Source                      DF       Squares     Mean Square    F Value    Pr > F

      Model                        3    3053.06354      1017.68785       3.37    0.0305

      Error                       32    9674.42389       302.32575

      Corrected Total             35   12727.48743


                    R-Square     Coeff Var      Root MSE    yield Mean

                    0.239880      1.522248      17.38752      1142.226


      Source                      DF      Anova SS     Mean Square    F Value    Pr > F

      temp                         3   3053.063542     1017.687847       3.37    0.0305
```

Table B.2.2. Data for acidity (pH) of pine wood bio-oil (refer Table 8).

Operating temperature (°C)	Iteration No.	Sample # 1	Sample # 2	Sample # 3
425	1	3.31	3.31	3.31
	2	3.33	3.34	3.33
	3	3.36	3.36	3.35
450	1	3.39	3.4	3.4
	2	3.43	3.43	3.43
	3	3.47	3.48	3.48
475	1	3.63	3.63	3.64
	2	3.69	3.68	3.68
	3	3.69	3.69	3.69
500	1	3.68	3.69	3.7
	2	3.74	3.73	3.73
	3	3.76	3.76	3.76

SAS code for acidity of pine wood bio-oil:

```
data Pinewood;
input temp pH;
datalines;
```

```
425    3.31
425    3.33
425    3.36
450    3.39
450    3.43
450    3.47
475    3.63
475    3.69
475    3.69
500    3.68
500    3.74
500    3.76
425    3.31
425    3.34
425    3.36
450    3.4
450    3.43
450    3.48
475    3.63
475    3.68
475    3.69
500    3.69
500    3.73
500    3.76
425    3.31
425    3.33
425    3.35
450    3.4
450    3.43
450    3.48
475    3.64
475    3.68
475    3.69
500    3.7
500    3.73
500    3.76
;
run;
proc anova data=Pinewood;
class temp;
model pH =temp;
means temp/ alpha=0.05;
run;
```

SAS result for acidity of pine wood bio-oil:

The ANOVA Procedure

Level of temp	N	pH Mean	pH Std Dev
425	9	3.33333333	0.02061553
450	9	3.43444444	0.03503966
475	9	3.66888889	0.02713137
500	9	3.72777778	0.03113590

```
Dependent Variable: pH
                                         Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F
      Model                        3       0.95148889      0.31716296     377.76    <.0001
      Error                       32       0.02686667      0.00083958
      Corrected Total             35       0.97835556
                       R-Square     Coeff Var      Root MSE    pH Mean
                       0.972539      0.818262      0.028976     3.541111
      Source                      DF         Anova SS     Mean Square    F Value    Pr > F
      temp                         3       0.95148889      0.31716296     377.76    <.0001
```

Table B.2.3. Data for water content of pine wood bio-oil (refer Table 8).

Sample	Sample wt (g)		Difference (g)	KFR vol (ml)		Difference (ml)	Water (wt%)
	Initial	Final		Initial	final		
methanol	0.0000	2.4000	2.4000				40ml
water			5 µl	2.4	3.3	0.9	5.56
water			5 µl	3.3	4.2	0.9	5.56
425-1-A	155.1438	155.0818	0.0620	0	2.2	2.2	19.71
425-1-B	155.0818	155.0151	0.0667	2.2	4.2	2	16.66
425-1-C	155.0151	154.9532	0.0619	4.2	6.2	2	17.95
425-2-A	156.7217	156.6661	0.0556	6.2	8.0	1.8	17.99
425-2-B	156.6650	156.6237	0.0413	8.0	9.6	1.6	21.52
425-2-C	156.6237	156.5786	0.0451	9.6	11.3	1.7	20.94
425-3-a	164.8720	164.8252	0.0468	11.3	13.0	1.7	20.18
425-3-b	164.8252	164.7893	0.0359	13.0	14.3	1.3	20.12
425-3-c	164.7893	164.7491	0.0402	14.3	15.9	1.6	22.11
450-3-a	133.6844	133.6321	0.0523	15.9	18.0	2.1	22.31
450-3-b	133.6321	133.5893	0.0428	18.0	19.5	1.5	19.47
450-3-c	133.5893	133.5352	0.0541	19.5	21.5	2	20.54
450-4-a	155.4381	155.3906	0.0475	21.5	23.1	1.6	18.71
450-4-b	155.3906	155.3230	0.0676	23.1	25.2	2.1	17.26
450-4-c	155.3230	155.2848	0.0382	25.2	26.5	1.3	18.91
450-5-a	164.1564	164.1139	0.0425	0.0	1.5	1.5	19.61
450-5-b	164.1139	164.0717	0.0422	1.5	2.9	1.4	18.43
450-5-c	164.0717	164.0259	0.0458	2.9	4.4	1.5	18.20
475-1-a	174.0000	173.9581	0.0419	0.0	1.5	1.5	19.89
475-1-b	173.9581	173.9168	0.0413	1.5	2.8	1.3	17.49
475-1-c	173.9168	173.8687	0.0481	2.8	4.3	1.5	17.33
475-2-a	127.9836	127.9176	0.0660	4.3	6.6	2.3	19.36
475-2-b	127.9176	127.8789	0.0387	6.6	8.0	1.4	20.10
475-2-c	127.8789	127.8338	0.0451	8.0	9.5	1.5	18.48
475-3a	161.3829	161.3238	0.0591	9.5	11.3	1.8	16.92
475-3b	161.3238	161.2730	0.0508	11.3	12.9	1.6	17.50

Sample	Sample wt (g)		Difference (g)	KFR vol (ml)		Difference (g)	Water (wt%)
	Initial	Final		Initial	final		
475-3c	161.2730	161.2218	0.0512	12.9	14.6	1.7	18.45
500-1a	138.2234	138.1800	0.0434	14.6	16.1	1.5	19.20
500-1b	138.1800	138.1381	0.0419	16.1	17.6	1.5	19.89
500-1c	138.1381	138.1030	0.0351	17.6	19.0	1.4	22.16
500.2a	168.7295	168.6684	0.0611	19.0	21.2	2.2	20.00
500-2b	168.6491	168.5373	0.1118	21.2	25.1	3.9	19.38
500-2c	168.5373	168.5015	0.0358	25.1	26.3	1.2	18.62
500-3a	165.3967	165.3506	0.0461	0.0	1.6	1.6	19.28
500-3b	165.3501	165.2971	0.0530	1.6	3.4	1.8	18.87
500-3c	165.2971	165.2369	0.0602	3.4	5.0	1.6	14.77

Water content calculations:

$$\text{Water (\%)} = \frac{\text{KFR required for sample titration (ml) x water equvalence of KFR x 0.1}}{\text{Grams of sample}}$$

SAS code for water content of pine wood bio-oil:

```
data Pinewood;
input temp Water;
datalines;
425    19.71327742
425    16.65835082
425    17.95011309
425    17.9856259
425    21.52275061
425    20.94113525
425    20.18045299
425    20.11762674
425    22.11168159
450    22.30721989
450    19.47042056
450    20.5381146
450    18.71346526
450    17.25839645
450    18.90635602
450    19.60785882
450    18.43076777
450    18.1950655
475    19.88863962
475    17.48723487
475    17.32503119
475    19.36028485
475    20.09763307
475    18.47747228
475    16.92048731
475    17.49782677
475    18.44619531
500    19.20124424
```

```
500   19.88863962
500   22.15892877
500   20.00365303
500   19.37986047
500   18.62198883
500   19.28177007
500   18.86793962
500   14.76560797
;
run;
proc anova data=Pinewood;
class temp;
model Water=temp;
means temp/ alpha=0.05;
run;
```

SAS result for water content of pine wood bio-oil:

```
                              The ANOVA Procedure

                   Level of             ------------Water------------
                   temp          N              Mean          Std Dev

                   425           9        19.6867794       1.81437687
                   450           9        19.2697405       1.47204990
                   475           9        18.3889784       1.17360386
                   500           9        19.1299592       1.93579512
Dependent Variable: Water

                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        3      7.90332978      2.63444326       1.00    0.4074

      Error                       32     84.66834495      2.64588578

      Corrected Total             35     92.57167474


                  R-Square     Coeff Var      Root MSE    Water Mean

                  0.085375      8.507921      1.626618      19.11886

      Source                      DF        Anova SS     Mean Square    F Value    Pr > F
      temp                         3      7.90332978      2.63444326       1.00    0.4074
```

Table B.2.4. Data for higher heating value of pine wood bio-oil (refer Table 8).

Operating temperature (°C)	Iteration No.	Weight of the sample #1	Energy required (J/g)	Weight of the sample #2	Energy required (J/g)	Weight of the sample #3	Energy required (J/g)
425	1	0.6027	19211	0.5427	19316	0.5638	19333
	2	0.5548	19513	0.4483	19692	0.5218	19717
	3	0.5246	20722	0.6735	20983	0.4732	21100
450	1	0.4892	20316	0.5531	20378	0.5063	20251
	2	0.5589	20692	0.5244	20523	0.5682	20547
	3	0.6273	21583	0.5298	21501	0.4893	21833
475	1	0.4611	20671	0.5231	20599	0.4439	20578
	2	0.5323	21456	0.4588	21382	0.6264	21504
	3	0.6653	21659	0.5442	21681	0.5538	21722
500	1	0.5683	21333	0.5462	21268	0.5183	21424
	2	0.654	22270	0.5483	22238	0.5032	22309
	3	0.5	22368	0.6093	22472	0.5333	22461

SAS code for higher heating value of pine wood bio-oil:

```
data Pinewood;
input temp HHV;
datalines;
425   19211
425   19513
425   20722
450   20316
450   20692
450   21583
475   20671
475   21456
475   21659
500   21333
500   22270
500   22368
425   19316
425   19692
425   20983
450   20378
450   20523
450   21501
475   20599
475   21382
475   21681
500   21268
500   22238
500   22472
425   19333
425   19717
```

```
425   21100
450   20251
450   20547
450   21833
475   20578
475   21504
475   21722
500   21424
500   22309
500   22461
;
run;
proc anova data=Pinewood;
class temp;
model HHV=temp;
means temp/ alpha=0.05;
run;
```

SAS result for higher heating value of pine wood bio-oil:

```
                                 The ANOVA Procedure

                        Level of          -------------HHV-------------
                        temp         N            Mean          Std Dev

                        425          9      19954.1111       760.428242
                        450          9      20847.1111       614.181049
                        475          9      21250.2222       488.726349
                        500          9      22015.8889       513.075395

Dependent Variable: HHV

                                            Sum of
      Source                      DF       Squares     Mean Square    F Value    Pr > F

      Model                        3    19896898.78     6632299.59      18.20    <.0001

      Error                       32    11660554.22      364392.32

      Corrected Total             35    31557453.00

                       R-Square     Coeff Var      Root MSE      HHV Mean

                       0.630498      2.872218      603.6492      21016.83

      Source                      DF       Anova SS    Mean Square    F Value    Pr > F

      temp                         3    19896898.78     6632299.59      18.20    <.0001
```

Table B.2.5. Data for ash content of pine wood bio-oil (refer Table 8).

Temp (°C)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	15.4957	15.4941	17.6575	2.1634	15.5045	0.0104	0.4807
	2	14.4295	14.4294	16.8598	2.4304	14.4431	0.0137	0.5636
	3	14.7354	14.7345	17.3163	2.5818	14.7553	0.0208	0.8056
450	1	14.9276	14.9272	17.1031	2.1759	14.9435	0.0163	0.7491
	2	14.9741	14.9735	17.8231	2.8496	15.0104	0.0369	1.2949
	3	14.3654	14.3643	17.2383	2.874	14.3923	0.028	0.9742
475	1	15.1804	15.1801	16.7278	1.5477	15.1968	0.0167	1.0790
	2	14.1305	14.1302	16.8136	2.6834	14.1498	0.0196	0.7304
	3	14.2178	14.2171	16.9395	2.7224	14.2392	0.0221	0.8117
500	1	14.2752	14.2747	16.927	2.6523	14.2799	0.0052	0.1960
	2	14.4982	14.4972	17.8152	3.318	14.5091	0.0119	0.3586
	3	14.8937	14.8931	17.4977	2.6046	14.9042	0.0111	0.4261

Temp (°C)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	14.7443	14.7434	17.2586	2.5152	14.7556	0.0122	0.4851
	2	13.7292	13.7286	15.5593	1.8307	13.7387	0.0101	0.5517
	3	15.3529	15.3528	17.6084	2.2556	15.3712	0.0184	0.8157
450	1	12.9885	12.9883	15.4689	2.4806	13.0096	0.0213	0.8587
	2	12.8962	12.8959	15.6154	2.7195	12.9301	0.0342	1.2576
	3	15.1207	15.1207	17.8644	2.7437	15.1476	0.0269	0.9804
475	1	14.3474	14.3467	17.6644	3.3177	14.3784	0.0317	0.9555
	2	15.0052	15.0044	17.2001	2.1957	15.021	0.0166	0.7560
	3	15.14	15.1377	17.4593	2.3216	15.1573	0.0196	0.8442
500	1	14.5044	14.5033	17.2331	2.7298	14.5084	0.0051	0.1868
	2	16.6669	16.666	17.9489	1.2829	16.6708	0.0048	0.3742
	3	15.4693	15.4689	18.1079	2.639	15.4805	0.0116	0.4396

Temp (°C)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	15.4959	15.4943	17.5999	2.1056	15.5037	0.0094	0.4464
	2	14.4298	14.429	15.9659	1.5369	14.4374	0.0084	0.5466
	3	14.7354	14.7345	16.1584	1.4239	14.7458	0.0113	0.7936
450	1	14.9276	14.9272	15.8834	0.9562	14.9351	0.0079	0.8262
	2	14.9742	14.9732	16.8698	1.8966	14.9957	0.0225	1.1863
	3	14.3659	14.3642	15.4801	1.1159	14.3743	0.0101	0.9051
475	1	15.1804	15.1806	16.081	0.9004	15.1891	0.0085	0.9440
	2	14.1309	14.131	15.5008	1.3698	14.1414	0.0104	0.7592
	3	14.2181	14.2171	15.876	1.6589	14.2308	0.0137	0.8258
500	1	14.2755	14.2745	15.5529	1.2784	14.2772	0.0027	0.2112
	2	14.4982	14.4975	15.8659	1.3684	14.5021	0.0046	0.3362
	3	14.8938	14.893	16.2628	1.3698	14.8992	0.0062	0.4526

SAS code for ash content of pine wood bio-oil:

```
data Pinewood;
input temp Ash;
datalines;
425    0.480724785
425    0.563693219
425    0.805639476
450    0.749115309
450    1.294918585
450    0.974251914
475    1.079020482
475    0.730416636
475    0.81178372
500    0.196056253
500    0.358649789
500    0.426169085
425    0.485050891
425    0.551701535
425    0.815747473
450    0.858663227
450    1.257584115
450    0.980427889
475    0.955481207
475    0.756023136
475    0.844245348
500    0.186826874
500    0.374152311
500    0.43956044
425    0.446428571
```

```
425   0.546554753
425   0.793595056
450   0.82618699
450   1.186333439
450   0.905099023
475   0.944024878
475   0.759234925
475   0.825848454
500   0.211201502
500   0.336159018
500   0.452620821
;
run;
proc anova data=Pinewood;
class temp;
model Ash=temp;
means temp/ alpha=0.05;
run;
```

SAS result for ash content of pine wood bio-oil:

```
                              The ANOVA Procedure

                        Level of          -------------Ash-------------
                        temp         N             Mean          Std Dev

                        425          9       0.60990397       0.15122921
                        450          9       1.00362005       0.19720267
                        475          9       0.85623098       0.11484498
                        500          9       0.33126623       0.10702461
Dependent Variable: Ash
                                             Sum of
      Source                      DF        Squares     Mean Square    F Value    Pr > F

      Model                        3     2.34607392      0.78202464      36.20    <.0001

      Error                       32     0.69122244      0.02160070

      Corrected Total             35     3.03729636


                       R-Square     Coeff Var      Root MSE      Ash Mean

                       0.772422      20.98831      0.146972      0.700255


      Source                      DF       Anova SS     Mean Square    F Value    Pr > F

      temp                         3     2.34607392      0.78202464      36.20    <.0001
```

Table B.2.6. Data for solid content of pine wood bio-oil (refer Table 8).

Operating temperature (°C)	Iteration No.	Sample #1				
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of the oil (g)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
425	1	320.2	308.3	0.9965	314.1	0.58
	2	327	315.2	1	320.5	0.53
	3	318.3	307.6	1.0006	315.3	0.77
450	1	325.9	316.4	1.0212	321.2	0.47
	2	321.1	311.9	1.0151	317.7	0.57
	3	321.6	312.5	1.0382	318.6	0.59
475	1	329.8	321.4	1.005	329.4	0.80
	2	326.5	317.9	0.9963	325	0.71
	3	321	312.7	1.0067	318.5	0.58
500	1	320.5	312.4	1.0165	314.7	0.23
	2	321.7	313.4	1.0072	320.1	0.67
	3	324.7	316.4	1.0029	324.6	0.82

Operating temperature (°C)	Iteration No.	Sample #2				
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of the oil (g)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
425	1	331	319.5	1.01	325.4	0.58
	2	327.3	315.9	1.0045	322	0.61
	3	328.5	317.6	1.0005	324.9	0.73
450	1	326.5	316.1	1.0375	321.3	0.50
	2	324.7	315.2	1.0191	320.5	0.52
	3	325.6	315.7	1.0041	321.8	0.61
475	1	333.1	325.3	0.9982	332.9	0.76
	2	324.1	317.7	0.9982	324.2	0.65
	3	319.5	311.3	1.0093	317.1	0.57
500	1	322.6	314.4	1.001	317.1	0.27
	2	323.9	315.6	1.0286	323.3	0.75
	3	330	320.5	1.0024	329	0.85

Operating temperature (°C)	Iteration No.	Sample #3				
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of the oil (g)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
425	1	329.4	321.8	1.0078	327.1	0.53
	2	325.1	317.5	1.0026	323.5	0.60
	3	342.9	330.3	0.9921	337.9	0.77
450	1	330.2	323.5	1.0164	328.5	0.49
	2	331.1	324.9	1.0311	331	0.59
	3	325.6	316.4	1.0026	322.7	0.63
475	1	322.8	314.9	1.0625	323.4	0.80
	2	341.7	333.1	1.0004	337.8	0.47
	3	343.8	337.5	1.0012	343.2	0.57
500	1	330.2	321.7	0.9994	324.6	0.29
	2	330.9	322.4	0.9812	329.4	0.71
	3	339.1	331.5	1.0269	339.3	0.76

Solid content calculations:

$$\text{Solid content (wt. \%)} = \frac{\text{Weight of filter paper after test} - \text{Weight of filter paper after drying}}{\text{Weight of the oil}\ \ \text{x 10}}$$

SAS code for solid content of pine wood bio-oil:

```
data Pinewood;
input temp Solid;
datalines;
425    0.58203713
425    0.53
425    0.769538277
450    0.470035253
450    0.571372279
450    0.587555384
475    0.7960199
475    0.712636756
475    0.576139863
500    0.226266601
500    0.665210485
500    0.817628876
425    0.584158416
425    0.607267297
425    0.729635182
450    0.501204819
450    0.520066726
450    0.607509212
475    0.761370467
475    0.65117211
```

```
475   0.574655702
500   0.26973027
500   0.748590317
500   0.847964884
425   0.525897996
425   0.598444045
425   0.766051809
450   0.49193231
450   0.591601203
450   0.628366248
475   0.8
475   0.469812075
475   0.56931682
500   0.290174104
500   0.713412148
500   0.759567631
;
run;
proc anova data=Pinewood;
class temp;
model Solid=temp;
means temp/ alpha=0.05;
run;
```

SAS result for solid content of pine wood bio-oil:

```
                              The ANOVA Procedure

                    Level of          ------------Solid-----------
                    temp         N            Mean          Std Dev

                    425          9      0.63255891       0.09656664
                    450          9      0.55218260       0.05705998
                    475          9      0.65679152       0.11717740
                    500          9      0.59317170       0.25441888
Dependent Variable: Solid
                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        3      0.05685645      0.01895215       0.83    0.4858

      Error                       32      0.72832377      0.02276012

      Corrected Total             35      0.78518022

                       R-Square     Coeff Var      Root MSE    Solid Mean

                       0.072412      24.78569      0.150865      0.608676
      Source                      DF        Anova SS     Mean Square    F Value    Pr > F
      temp                         3      0.05685645      0.01895215       0.83    0.4858
```

Table B.2.7. Data for density of underutilized forest bio-oil (refer Table 9).

Temp (°C)	Iteration No.	Sample #1				Sample #2				Sample #3			
		Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)	Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)	Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)
425	1	5838.9	8263	2424.1	1212.05	5835.5	8258.8	2423.3	1211.65	5842.1	8258.4	2416.3	1208.15
	2	5829.1	8191.3	2362.2	1181.1	5838.7	8192.9	2354.2	1177.1	5832.3	8200.6	2368.3	1184.15
	3	5824.2	8179.9	2355.7	1177.85	5828.5	8174.1	2345.6	1172.8	5837.1	8184.3	2347.2	1173.6
450	1	5830.1	8244.4	2414.3	1207.15	5842.7	8211.1	2368.4	1184.2	5844.9	8223.1	2378.2	1189.1
	2	5825.7	8175.4	2349.7	1174.85	5841.9	8205.9	2364	1182	5849.4	8223.3	2373.9	1186.95
	3	5811.7	8191.2	2379.5	1189.75	5845.8	8193.8	2348	1174	5832.1	8195.1	2363	1181.5
475	1	5826.7	8181.7	2355	1177.5	5832.1	8193.2	2361.1	1180.55	5837.5	8195.2	2357.7	1178.85
	2	5824.6	8216.3	2391.7	1195.85	5827.1	8196.9	2369.8	1184.9	5828.9	8227.8	2398.9	1199.45
	3	5828.2	8177.9	2349.7	1174.85	5837.1	8196.6	2359.5	1179.75	5849.8	8172.4	2322.6	1161.3
500	1	5833.6	8190.2	2356.6	1178.3	5850.2	8195.2	2345	1172.5	5872.8	8196.6	2323.8	1161.9
	2	5827	8188.3	2361.3	1180.65	5848	8207.8	2359.8	1179.9	5830.2	8195	2364.8	1182.4
	3	5828	8166.8	2338.8	1169.4	5822	8131.3	2309.3	1154.65	5817.3	8135.4	2318.1	1159.05

Note: Column “Iteration No.” represents the number of iterations made on the particular temperature and the columns Sample #1, #2 and #3 represents the experiments made on each Iteration No. Here, the column “Temp” represents the operating temperature (°C) of the process.

SAS code for density of underutilized forest bio-oil:

```
data UU;
input temp density;
datalines;
425   1212.05
425   1181.1
425   1177.85
450   1207.15
450   1174.85
450   1189.75
475   1177.5
475   1195.85
475   1174.85
500   1178.3
500   1180.65
500   1169.4
425   1211.65
425   1177.1
425   1172.8
450   1184.2
450   1182
450   1174
475   1180.55
475   1184.9
475   1179.75
500   1172.5
500   1179.9
500   1154.65
425   1208.15
425   1184.15
425   1173.6
450   1189.1
450   1186.95
450   1181.5
475   1178.85
475   1199.45
475   1161.3
500   1161.9
500   1182.4
500   1159.05
;
run;
proc anova data=UU;
class temp;
model density=temp;
means temp/ alpha=0.05;
run;
```

SAS result for density of underutilized forest bio-oil:

```
                         The ANOVA Procedure

              Level of          -----------density-----------
              temp         N             Mean          Std Dev
```

```
                425          9        1188.71667       16.8143912
                450          9        1185.50000        9.8581185
                475          9        1181.44444       11.2855395
                500          9        1170.97222       10.3278783

Dependent Variable: density

                                             Sum of
      Source                      DF        Squares     Mean Square    F Value    Pr > F

      Model                        3    1609.354722      536.451574       3.50    0.0267

      Error                       32    4911.477778      153.483681

      Corrected Total             35    6520.832500


                      R-Square     Coeff Var      Root MSE    density Mean

                      0.246802      1.048429      12.38885        1181.658


      Source                      DF       Anova SS     Mean Square    F Value    Pr > F

      temp                         3    1609.354722      536.451574       3.50    0.0267
```

Table B.2.8. Data for acidity (pH) of underutilized forest bio-oil (refer Table 9).

Operating temperature (°C)	Iteration No.	Sample # 1	Sample # 2	Sample # 3
425	1	3.01	3.01	3.01
	2	2.9	2.89	2.88
	3	2.91	2.9	2.9
450	1	3.08	3.07	3.07
	2	2.94	2.93	2.94
	3	2.92	2.92	2.91
475	1	3	3	2.99
	2	3.06	3.06	3.06
	3	3.08	3.08	3.05
500	1	3.06	3.06	3.06
	2	3.05	3.04	3.03
	3	3.19	3.19	3.18

SAS code for acidity (pH) of underutilized forest bio-oil:

```
data UU;
input temp pH;
datalines;
425    3.01
425    2.9
```

```
425    2.91
450    3.08
450    2.94
450    2.92
475    3
475    3.06
475    3.08
500    3.06
500    3.05
500    3.19
425    3.01
425    2.89
425    2.9
450    3.07
450    2.93
450    2.92
475    3
475    3.06
475    3.08
500    3.06
500    3.04
500    3.19
425    3.01
425    2.88
425    2.9
450    3.07
450    2.94
450    2.91
475    2.99
475    3.06
475    3.05
500    3.06
500    3.03
500    3.18
;
run;
proc anova data=UU;
class temp;
model pH=temp;
means temp/ alpha=0.05;
run;
```

SAS result for acidity (pH) of underutilized forest bio-oil:

```
                              The ANOVA Procedure
                    Level of          --------------pH-------------
                    temp         N             Mean          Std Dev

                    425          9       2.93444444       0.05725188
                    450          9       2.97555556       0.07401201
                    475          9       3.04222222       0.03562926
                    500          9       3.09555556       0.06912147

Dependent Variable: pH

                                              Sum of
     Source                      DF          Squares     Mean Square    F Value    Pr > F
```

```
Model                       3      0.13714167      0.04571389      12.35    <.0001
Error                      32      0.11842222      0.00370069
Corrected Total            35      0.25556389
                  R-Square     Coeff Var      Root MSE       pH Mean
                  0.536624      2.019736      0.060833      3.011944
Source                     DF        Anova SS     Mean Square    F Value    Pr > F
temp                        3      0.13714167      0.04571389      12.35    <.0001
```

Table B.2.9. Data for water content of underutilized forest bio-oil (refer Table 9).

Sample	Sample wt (g)		Difference (g)	KFR vol (ml)		Difference (ml)	Water (wt%)
	Initial	Final		Initial	final		
methanol	0.0000	2.4000	2.4000				40ml
water			5 µl	16	17.5	1.5	3.33
water			5 µl	17.5	19	1.5	3.33
425-1-A	32.5122	32.4787	0.0335	0	1.7	1.7	16.92
425-1-B	32.4787	32.4244	0.0543	1.7	4.7	3	18.42
425-1-C	32.4244	32.3839	0.0405	6.6	8.6	2	16.46
425-2-A	29.7094	29.6815	0.0279	8.6	10.3	1.7	20.31
425-2-B	29.6815	29.6538	0.0277	10.3	11.9	1.6	19.25
425-2-C	29.6537	29.6232	0.0305	11.9	13.8	1.9	20.77
425-3-a	28.6509	28.6161	0.0348	13.8	15.6	1.8	17.24
425-3-b	28.6161	28.586	0.0301	15.6	17.3	1.7	18.83
425-3-c	28.5853	28.5574	0.0279	17.3	18.6	1.3	15.53
450-1-a	29.7005	29.6705	0.03	5.7	7.4	1.7	18.89
450-1-b	29.6705	29.6527	0.0178	7.4	8.4	1	18.73
450-1-c	29.6526	29.6243	0.0283	8.4	9.8	1.4	16.49
450-2-a	28.2936	28.2661	0.0275	9.8	11.4	1.6	19.39
450-2-b	28.2661	28.2372	0.0289	11.4	12.9	1.5	17.30
450-2-c	28.237	28.2156	0.0214	12.9	14.1	1.2	18.69
450-3-a	31.4932	31.4444	0.0488	14.1	17	2.9	19.81
450-3-b	31.4444	31.374	0.0704	17	20.2	3.2	15.15
450-3-c	31.3739	31.2775	0.0964	20.2	25.4	5.2	17.98
475-1-a	29.9396	29.8607	0.0789	0	4.3	4.3	18.17
475-1-b	29.8604	29.8159	0.0445	4.3	6.5	2.2	16.48
475-1-c	29.8157	29.7878	0.0279	6.5	7.9	1.4	16.73
475-2-a	32.6278	32.5684	0.0594	7.9	10.5	2.6	14.59
475-2-b	32.5683	32.5224	0.0459	10.5	12.9	2.4	17.43
475-2-c	32.5224	32.4809	0.0415	12.9	15.1	2.2	17.67
475-3-a	28.5712	28.5341	0.0371	15.1	17.3	2.2	19.77
475-3-b	28.5341	28.4791	0.055	17.3	20.2	2.9	17.58
475-3-c	28.4789	28.4476	0.0313	20.2	21.9	1.7	18.10
500-1-a	32.2055	32.1481	0.0574	10.4	13.5	3.1	18.00

Sample	Sample wt (g)		Difference (g)	KFR vol (ml)		Difference (ml)	Water (wt%)
	Initial	Final		Initial	final		
500-1-b	31.4075	31.3402	0.0673	13.5	17.2	3.7	18.33
500-1-c	31.3402	31.293	0.0472	17.2	19.5	2.3	16.24
500-2-a	32.325	32.2765	0.0485	19.5	21.9	2.4	16.49
500-2-b	32.276	32.2241	0.0519	21.9	24.8	2.9	18.63
500-2-c	32.2241	32.1624	0.0617	0	3.3	3.3	17.83
500-3-a	33.0358	32.9541	0.0817	3.3	7.6	4.3	17.54
500-3-b	32.9568	32.8801	0.0767	7.6	11.4	3.8	16.51
500-3-c	32.879	32.724	0.155	11.4	20.1	8.7	18.71

SAS code for water content of underutilized forest bio-oil:

```
data UU;
input temp Water;
datalines;
425   16.91540597
425   18.41618785
425   16.46088889
425   20.3106129
425   19.2538917
425   20.76500656
425   17.24136207
425   18.82611628
425   15.53164516
450   18.88887
450   18.72657303
450   16.48997173
450   19.39392
450   17.30102076
450   18.69157009
450   19.80872336
450   15.1515
450   17.98061826
475   18.16643726
475   16.47938427
475   16.7263871
475   14.59033333
475   17.42917647
475   17.67066506
475   19.76637736
475   17.57574
475   18.10434824
500   18.00230488
500   18.32588559
500   16.24292161
500   16.49482887
500   18.62554335
500   17.82818314
500   17.54384211
500   16.51454237
```

```
500   18.70965871
;
run;
proc anova data=UU;
class temp;
model Water=temp;
means temp/ alpha=0.05;
run;
```

SAS result for water content of underutilized forest bio-oil:

```
                              The ANOVA Procedure

                 Level of         ------------Water------------
                 temp         N            Mean          Std Dev

                 425          9      18.1912353       1.77821870
                 450          9      18.0480852       1.49470048
                 475          9      17.3898721       1.41345592
                 500          9      17.5875234       0.95308343


Dependent Variable: Water

                                        Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F

      Model                        3       3.85103382      1.28367794       0.62    0.6082

      Error                       32      66.41933546      2.07560423

      Corrected Total             35      70.27036928


                      R-Square     Coeff Var      Root MSE    Water Mean

                      0.054803      8.091897      1.440696      17.80418


      Source                      DF         Anova SS     Mean Square    F Value    Pr > F

      temp                         3       3.85103382      1.28367794       0.62    0.6082
```

Table B.2.10. Data for higher heating value of underutilized forest bio-oil (refer Table 9).

Operating temperature (°C)	Iteration No.	Weight of the sample #1	Energy required (J/g)	Weight of the sample #2	Energy required (J/g)	Weight of the sample #3	Energy required (J/g)
425	1	0.5063	17210	0.5129	19120	0.5065	18942
	2	0.6272	19486	0.5207	20202	0.5405	20760
	3	0.5259	20135	0.5679	20676	0.5486	19256
450	1	0.5621	19271	0.4969	20887	0.5514	20948
	2	0.5478	20380	0.5456	20137	0.5546	20479
	3	0.5348	21103	0.554	20186	0.5213	21077
475	1	0.55	20108	0.5358	21145	0.5331	21320
	2	0.5674	19808	0.5	19797	0.5128	21441
	3	0.5328	19297	0.5362	20321	0.5539	20553
500	1	0.5535	18694	0.5485	19162	0.5135	19654
	2	0.5321	18908	0.547	18777	0.5262	18999
	3	0.6444	19975	0.5373	21532	0.5058	21471

SAS code for higher heating value of underutilized forest bio-oil:

```
data UU;
input temp HHV;
datalines;
425   17210
425   19486
425   20135
450   19271
450   20380
450   21103
475   20108
475   19808
475   19297
500   18694
500   18908
500   19975
425   19120
425   20202
425   20676
450   20887
450   20137
450   20186
475   21145
475   19797
475   20321
500   19162
500   18777
500   21532
425   18942
425   20760
```

```
425    19256
450    20948
450    20479
450    21077
475    21320
475    21441
475    20553
500    19654
500    18999
500    21471
;
run;
proc anova data=UU;
class temp;
model HHV=temp;
means temp/ alpha=0.05;
run;
```

SAS result for higher heating value of underutilized forest bio-oil:

```
                                   The ANOVA Procedure

                        Level of          -------------HHV-------------
                        temp          N             Mean          Std Dev

                        425           9       19531.8889       1096.41740
                        450           9       20496.4444        591.87670
                        475           9       20421.1111        752.22095
                        500           9       19685.7778       1109.09082


Dependent Variable: HHV

                                                 Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F

      Model                        3       6633756.08      2211252.03       2.64    0.0662

      Error                       32      26786943.56       837091.99

      Corrected Total             35      33420699.64


                       R-Square     Coeff Var      Root MSE      HHV Mean

                       0.198492      4.566917      914.9273      20033.81


      Source                      DF         Anova SS     Mean Square    F Value    Pr > F

      temp                         3      6633756.083     2211252.028       2.64    0.0662
```

Table B.2.11. Data for ash content of underutilized forest bio-oil (refer Table 9).

Temp (°C)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	18.2134	18.1385	21.1051	2.9666	18.1779	0.0394	1.3281
	2	17.8299	17.8283	20.9281	3.0998	17.8568	0.0285	0.9194
	3	18.1687	18.1621	21.1985	3.0364	18.1875	0.0254	0.8365
450	1	17.3581	17.3438	20.65	3.3062	17.3707	0.0269	0.8136
	2	17.7969	17.7921	21.9604	4.1683	17.8269	0.0348	0.8349
	3	17.766	17.7653	20.9845	3.2192	17.7807	0.0154	0.4784
475	1	17.7151	17.7126	20.7595	3.0469	17.742	0.0294	0.9649
	2	18.1468	18.1385	20.5214	2.3829	18.1593	0.0208	0.8729
	3	17.8307	17.8283	20.7462	2.9179	17.8569	0.0286	0.9802
500	1	17.7598	17.7592	20.096	2.3368	17.7751	0.0159	0.6804
	2	17.6159	17.6149	19.042	1.4271	17.6231	0.0082	0.5746
	3	17.7944	17.7921	20.5628	2.7707	17.8059	0.0138	0.4981

Temp (°C)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	17.9597	17.958	21.2016	3.2436	18.0016	0.0436	1.3442
	2	18.3781	18.3778	21.1871	2.8093	18.4011	0.0233	0.8294
	3	17.7768	17.7653	20.6952	2.9299	17.7837	0.0184	0.6280
450	1	17.9504	17.9421	21.0578	3.1157	17.9697	0.0276	0.8858
	2	17.7622	17.7592	21.5	3.7408	17.7868	0.0276	0.7378
	3	17.4219	17.4206	20.5478	3.1272	17.4352	0.0146	0.4669
475	1	17.4228	17.4206	20.0672	2.6466	17.4535	0.0329	1.2431
	2	17.9599	17.958	20.794	2.836	17.9826	0.0246	0.8674
	3	18.384	18.3778	20.629	2.2512	18.4034	0.0256	1.1372
500	1	17.9561	17.9552	20.0313	2.0761	17.9703	0.0151	0.7273
	2	17.5198	17.5159	20.1673	2.6514	17.5352	0.0193	0.7279
	3	17.7651	17.7653	20.0261	2.2608	17.7748	0.0095	0.4202

Temp (°C)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	17.7012	17.6999	19.9564	2.2565	17.7184	0.0185	0.8199
	2	18.1382	18.1369	20.4025	2.2656	18.1584	0.0215	0.9490
	3	17.4256	17.4231	20.4627	3.0396	17.4437	0.0206	0.6777
450	1	18.3779	18.3772	20.4516	2.0744	18.3968	0.0196	0.9449
	2	17.7184	17.7115	19.7638	2.0523	17.7255	0.014	0.6822
	3	17.345	17.3439	19.6766	2.3327	17.3566	0.0127	0.5444
475	1	17.7602	17.7586	19.58	1.8214	17.7824	0.0238	1.3067
	2	17.9609	17.9555	19.884	1.9285	17.974	0.0185	0.9593
	3	18.1666	18.1613	19.9658	1.8045	18.1835	0.0222	1.2303
500	1	17.4273	17.4238	19.866	2.4422	17.4425	0.0187	0.7657
	2	17.7054	17.7	20.7765	3.0765	17.7213	0.0213	0.6923
	3	17.7155	17.7112	19.9874	2.2762	17.723	0.0118	0.5184

SAS code for ash content of underutilized forest bio-oil:

```
data UU;
input temp Ash;
datalines;
425   1.328119733
425   0.919414156
425   0.836516928
450   0.81362289
450   0.83487273
450   0.478379722
475   0.96491516
475   0.872885979
475   0.980156962
500   0.680417665
500   0.57459183
500   0.49806908
425   1.344185473
425   0.829388104
425   0.628007782
450   0.885836249
450   0.737810094
450   0.466871323
475   1.24310436
475   0.8674189
475   1.137171286
500   0.727325273
500   0.727917327
500   0.420205237
```

```
425   0.819853756
425   0.948975989
425   0.677720753
450   0.944851523
450   0.682161477
450   0.544433489
475   1.306687164
475   0.959294789
475   1.230257689
500   0.765703055
500   0.692345197
500   0.518407873
;
run;
proc anova data=UU;
class temp;
model Ash=temp;
means temp/ alpha=0.05;
run;
```

SAS result for ash content of underutilized forest bio-oil:

```
                              The ANOVA Procedure

                  Level of          -------------Ash-------------
                  temp         N            Mean          Std Dev

                  425          9      0.92579807       0.25401780
                  450          9      0.70987106       0.17822897
                  475          9      1.06243248       0.16842220
                  500          9      0.62277584       0.12266671

Dependent Variable: Ash

                                           Sum of
      Source                      DF      Squares     Mean Square    F Value    Pr > F

      Model                        3   1.08517277      0.36172426      10.36    <.0001

      Error                       32   1.11763015      0.03492594

      Corrected Total             35   2.20280292

                       R-Square     Coeff Var      Root MSE      Ash Mean

                       0.492633      22.51030      0.186885      0.830219

      Source                      DF     Anova SS     Mean Square    F Value    Pr > F

      temp                         3   1.08517277      0.36172426      10.36    <.0001
```

Table B.2.12. Data for solid content of underutilized forest bio-oil (refer Table 9).

Operating temperature (°C)	Iteration No.	Sample #1				
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of the oil (g)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
425	1	560.1	544.3	1.018	548.3	0.39
	2	560.3	545.1	1.2174	548.1	0.25
	3	565.1	551.4	1.0393	554.3	0.28
450	1	566.8	539.8	1.099	544.9	0.46
	2	553.5	538.2	1.0196	541.8	0.35
	3	557	547.1	1.0383	551.6	0.43
475	1	564	538.7	1.0764	544.5	0.54
	2	566.8	540.1	1.0123	545.2	0.50
	3	563.3	534.6	1.0108	540.8	0.61
500	1	557.9	537.3	1.0053	542.2	0.49
	2	560.2	539.8	1.0275	544.9	0.50
	3	561.1	536	1.0831	541.1	0.47

Operating temperature (°C)	Iteration No.	Sample #2				
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of the oil (g)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
425	1	558.5	542	1.0235	547.1	0.50
	2	560.9	537.7	1.0092	539.6	0.19
	3	558.1	530.1	1.0258	532.3	0.21
450	1	557.6	543.7	1.0367	549.1	0.52
	2	556	539.8	1.008	543.3	0.35
	3	549.4	537.9	1.0798	543.3	0.50
475	1	562.3	542.7	1.039	547.4	0.45
	2	567.7	542.9	1.0084	547.8	0.49
	3	572.9	549.1	1.0293	555.6	0.63
500	1	561.8	540.8	1.0111	546.4	0.55
	2	562.1	534.6	1	539.6	0.50
	3	565.2	539.1	1.0217	544.8	0.56

Operating temperature (°C)	Iteration No.	Sample #3				
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of the oil (g)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
425	1	568.1	548.7	1.0195	552.9	0.41
	2	575	554.3	1	555.6	0.13
	3	558.4	540.8	1.0903	542.9	0.19
450	1	570.1	545.9	1.0113	549.9	0.40
	2	562.1	552.2	1.0329	556.4	0.41
	3	551	539.9	1.0019	544	0.41
475	1	564.6	537.9	1.0465	543.3	0.52
	2	555.2	528.5	1.0112	533.1	0.45
	3	563.1	541	1.0431	547.1	0.58
500	1	564.7	539	1.1231	543.8	0.43
	2	568.3	540	1.0662	545.9	0.55
	3	554.5	529.1	1.0646	534.9	0.54

SAS code for solid content of underutilized forest bio-oil:

```
data UU;
input temp Solid;
datalines;
425	0.392927308
425	0.246426811
425	0.279033965
450	0.464058235
450	0.353079639
450	0.433400751
475	0.538833148
475	0.50380322
475	0.613375544
500	0.487416692
500	0.496350365
500	0.470870649
425	0.498290181
425	0.188267935
425	0.214466758
450	0.520883573
450	0.347222222
450	0.50009261
475	0.452358037
475	0.485918286
475	0.631497134
500	0.55385224
500	0.5
500	0.557893707
425	0.41196665
425	0.13
425	0.192607539
```

```
450   0.395530505
450   0.406622132
450   0.409222477
475   0.516005733
475   0.454905063
475   0.584795322
500   0.427388478
500   0.553367098
500   0.544805561
;
run;
proc anova data=UU;
class temp;
model Solid=temp;
means temp/ alpha=0.05;
run;
```

SAS result for solid content of underutilized forest bio-oil:

```
                                   The ANOVA Procedure

                        Level of          ------------Solid------------
                        temp         N            Mean          Std Dev

                        425          9      0.28377635       0.12332120
                        450          9      0.42556802       0.06031462
                        475          9      0.53127683       0.06596577
                        500          9      0.51021609       0.04536054

Dependent Variable: Solid

                                               Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F

      Model                        3       0.34069393      0.11356464      17.99    <.0001

      Error                       32       0.20204025      0.00631376

      Corrected Total             35       0.54273418


                       R-Square     Coeff Var      Root MSE    Solid Mean

                       0.627736      18.15341      0.079459      0.437709


      Source                      DF         Anova SS     Mean Square    F Value    Pr > F

      temp                         3       0.34069393      0.11356464      17.99    <.0001
```

Table B.2.13. Data for density of poultry litter bio-oil (refer Table 10).

Temp (°C)	Iteration No.	Sample #1				Sample #2				Sample #3			
		Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)	Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)	Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)
425	1	5.7328	7.8422	2.1094	1054.7	5.75	7.8583	2.1083	1054.15	5.7341	7.8429	2.1088	1054.4
	2	5.7435	7.8594	2.1159	1057.95	5.7619	7.8637	2.1018	1050.9	5.7487	7.8584	2.1097	1054.85
	3	5.7429	8.0179	2.275	1137.5	5.7429	8.011	2.2681	1134.05	5.7454	8.0169	2.2715	1135.75
450	1	5.7602	7.8768	2.1166	1058.3	5.7793	7.8827	2.1034	1051.7	5.76	7.8738	2.1138	1056.9
	2	5.8031	7.9119	2.1088	1054.4	5.8046	7.9165	2.1119	1055.95	5.8078	7.9127	2.1049	1052.45
	3	5.7604	7.9359	2.1755	1087.75	5.8114	7.9736	2.1622	1081.1	5.7665	7.9364	2.1699	1084.95
475	1	5.7523	7.8703	2.118	1059	5.917	8.0154	2.0984	1049.2	5.7412	7.8665	2.1253	1062.65
	2	5.757	7.9113	2.1543	1077.15	5.7865	7.9451	2.1586	1079.3	5.7589	7.898	2.1391	1069.55
	3	5.7624	7.8976	2.1352	1067.6	5.8239	7.9145	2.0906	1045.3	5.7687	7.8877	2.119	1059.5
500	1	5.7455	7.8697	2.1242	1062.1	5.7679	7.888	2.1201	1060.05	5.7398	7.871	2.1312	1065.6
	2	5.7554	7.8835	2.1281	1064.05	5.7775	7.9004	2.1229	1061.45	5.7501	7.8629	2.1128	1056.4
	3	5.7509	7.875	2.1241	1062.05	5.8174	7.9459	2.1285	1064.25	5.7596	7.8905	2.1309	1065.45

SAS code for density of poultry litter bio-oil:

```
data PL;
input temp Density;
datalines;
425    1054.7
425    1057.95
425    1137.5
450    1058.3
450    1054.4
450    1087.75
475    1059
475    1077.15
475    1067.6
500    1062.1
500    1064.05
500    1062.05
425    1054.15
425    1050.9
425    1134.05
450    1051.7
450    1055.95
450    1081.1
475    1049.2
475    1079.3
475    1045.3
500    1060.05
500    1061.45
500    1064.25
425    1054.4
425    1054.85
425    1135.75
450    1056.9
450    1052.45
450    1084.95
475    1062.65
475    1069.55
475    1059.5
500    1065.6
500    1056.4
500    1065.45
;
run;
proc anova data=PL;
class temp;
model Density=temp;
means temp/ alpha=0.05;
run;
```

SAS result for density of poultry litter bio-oil:

```
                              The ANOVA Procedure

                 Level of          -----------Density-----------
                 temp         N             Mean          Std Dev
```

```
              425           9         1081.58333        40.6853168
              450           9         1064.83333        15.0568921
              475           9         1063.25000        11.5190874
              500           9         1062.37778         2.9223397

Dependent Variable: Density

                                                Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F

      Model                        3       2238.35500       746.11833       1.48    0.2399

      Error                       32      16185.87556       505.80861

      Corrected Total             35      18424.23056


                     R-Square     Coeff Var      Root MSE    Density Mean

                     0.121490      2.105801      22.49019        1068.011


      Source                      DF         Anova SS     Mean Square    F Value    Pr > F

      temp                         3      2238.355000      746.118333       1.48    0.2399
```

Table B.2.14. Data for acidity (pH) of poultry litter bio-oil (refer Table 10).

Operating temperature (°C)	Iteration No.	Sample # 1	Sample # 2	Sample # 3
425	1	9.23	9.23	9.25
	2	9.28	9.28	9.27
	3	9.24	9.23	9.23
450	1	9.31	9.31	9.31
	2	9.32	9.31	9.32
	3	9.28	9.29	9.29
475	1	9.31	9.31	9.31
	2	9.35	9.35	9.34
	3	9.33	9.34	9.34
500	1	9.36	9.36	9.36
	2	9.44	9.44	9.44
	3	9.48	9.49	9.49

SAS code for acidity (pH) of poultry litter bio-oil:

```
data PL;
input temp pH;
datalines;
```

```
425    9.23
425    9.28
425    9.24
450    9.31
450    9.32
450    9.28
475    9.31
475    9.35
475    9.33
500    9.36
500    9.44
500    9.48
425    9.23
425    9.28
425    9.23
450    9.31
450    9.31
450    9.29
475    9.31
475    9.35
475    9.34
500    9.36
500    9.44
500    9.49
425    9.25
425    9.27
425    9.23
450    9.31
450    9.32
450    9.29
475    9.31
475    9.34
475    9.34
500    9.36
500    9.44
500    9.49
;
run;
proc anova data=PL;
class temp;
model pH=temp;
means temp/ alpha=0.05;
run;
quit;
proc boxplot data=PL;
plot pH*temp /boxstyle=schematic;
run;
```

SAS result for acidity (pH) of poultry litter bio-oil:

```
                        The ANOVA Procedure

            Level of        --------------pH-------------
            temp        N           Mean          Std Dev

            425         9     9.24888889       0.02204793
```

```
                  450          9       9.30444444       0.01424001
                  475          9       9.33111111       0.01691482
                  500          9       9.42888889       0.05555278
Dependent Variable: pH
                                         Sum of
      Source                   DF        Squares     Mean Square    F Value    Pr > F
      Model                     3     0.15301111      0.05100370      50.24    <.0001
      Error                    32     0.03248889      0.00101528
      Corrected Total          35     0.18550000
                      R-Square     Coeff Var      Root MSE       pH Mean
                      0.824858      0.341577      0.031863      9.328333

 Source                     DF       Anova SS     Mean Square    F Value    Pr > F
 temp                        3     0.15301111      0.05100370      50.24    <.0001
```

Table B.2.15. Data for water content of poultry litter bio-oil (refer Table 10).

Sample	Sample wt (g)		Difference (g)	KFR vol (ml)		Difference (ml)	Water (wt%)
	Initial	Final		Initial	final		
methanol	0.0000	20.6000	20.6000				40ml
water			5 µl	1.6	3.1	1.5	3.33
water			5 µl	3.1	4.6	1.5	3.33
425-1-A	106.3119	106.2718	0.0401	0	4.7	4.7	38.26
425-1-B	106.2715	106.2290	0.0425	4.7	9.3	4.6	35.33
425-1-C	106.2290	106.1703	0.0587	9.3	15.8	6.5	36.14
425-2-A	158.9371	158.8778	0.0593	15.8	21.7	5.9	32.47
425-2-B	158.8778	158.8326	0.0452	21.7	26.3	4.6	33.22
425-2-C	158.8326	158.7878	0.0448	0	4.5	4.5	32.78
425-3-a	153.6570	153.6235	0.0335	4.5	8.4	3.9	38.00
425-3-b	153.6235	153.5800	0.0435	8.4	12.8	4.4	33.01
425-3-c	153.5800	153.5470	0.0330	12.8	16.3	3.5	34.62
450-3-a	117.6800	117.6355	0.0445	16.3	21.0	4.7	34.47
450-3-b	117.6355	117.5941	0.0414	21.0	25.3	4.3	33.90
450-3-c	117.5941	117.5310	0.0631	0.0	5.9	5.9	30.52
450-4-a	159.3223	159.2871	0.0352	5.9	8.9	3	27.82
450-4-b	159.2855	159.1960	0.0895	8.9	16.7	7.8	28.45
450-4-c	159.1940	159.1320	0.0620	16.7	22.1	5.4	28.43
450-5-a	159.6726	159.6374	0.0352	0.0	3.2	3.2	29.67
450-5-b	159.6374	159.5743	0.0631	3.2	9.4	6.2	32.07
450-5-c	159.5743	159.5359	0.0384	9.4	13.1	3.7	31.45
475-1-a	114.5225	114.4844	0.0381	13.1	16.8	3.7	31.70
475-1-b	114.4831	114.4485	0.0346	16.8	19.9	3.1	29.24
475-1-c	114.4142	114.3773	0.0369	19.9	23.1	3.2	28.30
475-2-a	159.6025	159.5615	0.0410	0.0	3.7	3.7	29.45

Sample	Sample wt (g)		Difference (g)	KFR vol (ml)		Difference (ml)	Water (wt%)
	Initial	Final		Initial	final		
475-2-b	159.2795	159.2478	0.0317	3.7	6.3	2.6	26.77
475-2-c	159.2478	159.2110	0.0368	6.3	9.5	3.2	28.38
475-3a	155.6700	155.6323	0.0377	9.5	12.6	3.1	26.84
475-3b	155.6304	155.5853	0.0451	12.6	16.7	4.1	29.67
475-3c	155.5845	155.5521	0.0324	16.7	19.9	3.2	32.24
500-1a	160.4940	160.4598	0.0342	0.0	3.0	3	28.63
500-1b	160.4498	160.4243	0.0255	3.0	5.5	2.5	32.00
500-1c	160.4235	160.3956	0.0279	5.5	8.1	2.6	30.42
500.2a	93.9595	93.9126	0.0469	8.1	11.8	3.7	25.75
500-2b	93.9126	93.8715	0.0411	11.8	15.6	3.8	30.18
500-2c	93.8715	93.8273	0.0442	15.6	19.3	3.7	27.32
500-3a	116.8931	116.8465	0.0466	19.3	23.3	4	28.02
500-3b	116.8457	116.7943	0.0514	0.0	4.6	4.6	29.21
500-3c	116.7943	116.7545	0.0398	4.6	8.3	3.7	30.34

SAS code for water content of poultry litter bio-oil:

```
data PL;
input temp Water;
datalines;
425    38.25518703
425    35.32691765
425    36.14199319
425    32.47387858
425    33.21668142
425    32.78470982
425    37.99764179
425    33.01416092
425    34.61712121
450    34.47265169
450    33.90041063
450    30.51824089
450    27.81732955
450    28.44516201
450    28.42751613
450    29.67181818
450    32.07001585
450    31.44903646
475    31.69666667
475    29.24303468
475    28.30482385
475    29.45470732
475    26.77015773
475    28.38173913
475    26.83843501
475    29.67181818
475    32.23604938
```

```
500    28.63070175
500    31.99901961
500    30.4162724
500    25.7493177
500    30.17717762
500    27.32223982
500    28.01630901
500    29.21
500    30.34278894
;
run;
proc anova data=PL;
class temp;
model Water=temp;
means temp/ alpha=0.05;
run;
```

SAS result for water content of poultry litter bio-oil:

```
                                The ANOVA Procedure

                        Level of           ------------Water------------
                        temp          N            Mean          Std Dev

                        425           9      34.8698102       2.21922724
                        450           9      30.7524646       2.41187727
                        475           9      29.1774924       1.89366493
                        500           9      29.0959808       1.89195033


Dependent Variable: Water

                                                Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F

      Model                        3      197.8272949      65.9424316      14.73    <.0001

      Error                       32      143.2605153       4.4768911

      Corrected Total             35      341.0878103


                       R-Square     Coeff Var      Root MSE    Water Mean

                       0.579989      6.831119      2.115867      30.97394


      Source                      DF         Anova SS     Mean Square    F Value    Pr > F

      temp                         3      197.8272949      65.9424316      14.73    <.0001
```

Table B.2.16. Data for higher heating value of poultry litter bio-oil (refer Table 10).

Operating temperature (°C)	Iteration No.	Weight of the sample #1	Energy required (J/g)	Weight of the sample #2	Energy required (J/g)	Weight of the sample #3	Energy required (J/g)
425	1	0.5132	10.947	0.6725	10.754	0.4891	10.823
	2	0.5165	11.124	0.5189	10.459	0.567	11.93
	3	0.5128	11.004	0.5276	11.859	0.5681	11.828
450	1	0.6136	11.369	0.5471	12.98	0.4923	12.797
	2	0.596	12.341	0.5701	12.329	0.6549	11.109
	3	0.5471	13.441	0.5287	12.965	0.6194	12.872
475	1	0.5978	14.217	0.5219	13.491	0.5418	13.675
	2	0.6	14.456	0.6289	14.36	0.5218	14.673
	3	0.4912	14.298	0.5172	14.112	0.5732	14.365
500	1	0.526	14.324	0.5872	14.561	0.5174	13.673
	2	0.6564	13.741	0.4398	13.786	0.4561	13.101
	3	0.5436	13.79	0.558	14.39	0.5926	13.682

SAS code for higher heating value of poultry litter bio-oil:

```
data PL;
input temp HHV;
datalines;
425    10.947
425    11.124
425    11.004
450    11.369
450    12.341
450    13.441
475    14.217
475    14.456
475    14.298
500    14.324
500    13.741
500    13.79
425    10.754
425    10.459
425    11.859
450    12.98
450    12.329
450    12.965
475    13.491
475    14.36
475    14.112
500    14.561
500    13.786
500    14.39
425    10.823
425    11.93
```

```
425   11.828
450   12.797
450   11.109
450   12.872
475   13.675
475   14.673
475   14.365
500   13.673
500   13.101
500   13.682
;
run;
proc anova data=PL;
class temp;
model HHV=temp;
means temp/ alpha=0.05;
run;
```

SAS result for higher heating value of poultry litter bio-oil:

The ANOVA Procedure

Level of temp	N	HHV Mean	HHV Std Dev
425	9	11.1920000	0.54306031
450	9	12.4670000	0.77600435
475	9	14.1830000	0.37673465
500	9	13.8942222	0.45336624

Dependent Variable: HHV

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	51.61212633	17.20404211	55.29	<.0001
Error	32	9.95653756	0.31114180		
Corrected Total	35	61.56866389			

R-Square	Coeff Var	Root MSE	HHV Mean
0.838286	4.312652	0.557801	12.93406

Source	DF	Anova SS	Mean Square	F Value	Pr > F
temp	3	51.61212633	17.20404211	55.29	<.0001

Table B.2.17. Data for ash content of poultry litter bio-oil (refer Table 10).

Temp (°C)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	18.1413	18.1405	20.1504	2.0099	18.1423	0.0018	0.0896
	2	18.1652	18.1634	19.8829	1.7195	18.1656	0.0022	0.1279
	3	17.7629	17.7623	20.4962	2.7339	17.7649	0.0026	0.0951
450	1	17.6202	17.6187	19.6552	2.0365	17.6216	0.0029	0.1424
	2	17.9619	17.9614	20.0976	2.1362	17.9653	0.0039	0.1826
	3	17.3471	17.3457	18.6967	1.3510	17.3482	0.0025	0.1850
475	1	17.4279	17.4256	18.9114	1.4858	17.4286	0.0030	0.2019
	2	17.9451	17.9454	19.8191	1.8737	17.9492	0.0038	0.2028
	3	12.7336	12.7336	14.1935	1.4599	12.7363	0.0027	0.1849
500	1	9.7761	9.7752	10.6453	0.8701	9.7764	0.0012	0.1379
	2	9.4736	9.4728	10.2990	0.8262	9.4741	0.0013	0.1573
	3	12.1083	12.1074	12.9368	0.8294	12.1085	0.0011	0.1326

Temp (°C)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	18.3810	18.3806	20.2131	1.8325	18.3823	0.0017	0.0928
	2	17.5189	17.5182	19.4173	1.8991	17.5202	0.0020	0.1053
	3	17.9607	17.9596	21.1111	3.1515	17.9622	0.0026	0.0825
450	1	17.7982	17.7966	19.9944	2.1978	17.7999	0.0033	0.1502
	2	17.7677	17.7673	18.6567	0.8894	17.7690	0.0017	0.1911
	3	17.4231	17.4227	19.0469	1.6242	17.4255	0.0028	0.1724
475	1	17.7033	17.7033	18.8232	1.1199	17.7055	0.0022	0.1964
	2	17.7141	17.7137	19.5260	1.8123	17.7175	0.0038	0.2097
	3	11.9863	11.9862	14.5276	2.5414	11.9919	0.0057	0.2243
500	1	9.6727	9.6724	10.2071	0.5347	9.6731	0.0007	0.1309
	2	12.4191	12.4189	13.7764	1.3575	12.4211	0.0022	0.1621
	3	13.0795	13.0790	15.2365	2.1575	13.0821	0.0031	0.1437

Temp (°C)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	18.1413	18.1405	20.0973	1.9568	18.1427	0.0022	0.1124
	2	18.1652	18.1634	19.4390	1.2756	18.1649	0.0015	0.1176
	3	17.7629	17.7623	20.9561	3.1938	17.7647	0.0024	0.0751
450	1	17.6202	17.6187	19.5389	1.9202	17.6213	0.0026	0.1354
	2	17.9619	17.9614	20.2583	2.2969	17.9656	0.0042	0.1829
	3	17.3471	17.3457	18.4569	1.1112	17.3476	0.0019	0.1710
475	1	17.4279	17.4256	18.3893	0.9637	17.4275	0.0019	0.1972
	2	17.9451	17.9454	20.6739	2.7285	17.9507	0.0053	0.1942
	3	12.7336	12.7336	14.5009	1.7673	12.7371	0.0035	0.1980
500	1	9.7761	9.7752	10.2945	0.5193	9.7759	0.0007	0.1348
	2	9.4736	9.4728	10.7893	1.3165	9.4751	0.0023	0.1747
	3	12.1083	12.1074	13.0002	0.8928	12.1087	0.0013	0.1456

SAS code for ash content of poultry litter bio-oil:

```
data PL;
input temp Ash;
datalines;
425   0.089556694
425   0.12794417
425   0.095102235
450   0.142401178
450   0.182567175
450   0.185048113
475   0.201911428
475   0.20280728
475   0.184944174
500   0.137915182
500   0.157346889
500   0.132625995
425   0.092769441
425   0.105313043
425   0.082500397
450   0.15015015
450   0.191140094
450   0.172392562
475   0.196446111
475   0.209678309
475   0.224285827
500   0.130914532
500   0.162062615
500   0.14368482
```

```
425   0.112428455
425   0.117591722
425   0.075145595
450   0.135402562
450   0.182855153
450   0.170986321
475   0.197156792
475   0.194245923
475   0.198042211
500   0.134796842
500   0.174705659
500   0.145609319
;
run;
proc anova data=PL;
class temp;
model Ash=temp;
means temp/ alpha=0.05;
run;
```

SAS result for ash content of poultry litter bio-oil:

```
                                  The ANOVA Procedure

                        Level of           -------------Ash-------------
                        temp         N             Mean          Std Dev

                        425          9       0.09981686       0.01725561
                        450          9       0.16810481       0.02038260
                        475          9       0.20105756       0.01100723
                        500          9       0.14662909       0.01504176
Dependent Variable: Ash

                                             Sum of
      Source                      DF        Squares     Mean Square    F Value    Pr > F

      Model                        3     0.04863118      0.01621039      61.14    <.0001

      Error                       32     0.00848496      0.00026516

      Corrected Total             35     0.05711614

                       R-Square     Coeff Var      Root MSE      Ash Mean

                       0.851444      10.58048      0.016284      0.153902


      Source                      DF       Anova SS     Mean Square    F Value    Pr > F

      temp                         3     0.04863118      0.01621039      61.14    <.0001
```

Table B.2.18. Data for solid content of poultry litter bio-oil (refer Table 10).

Operating temperature (°C)	Iteration No.	Sample #1				
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of the oil (g)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
425	1	325.7	317	1.0345	317.9	0.09
	2	322.4	314.7	1.0068	316	0.13
	3	337.6	328.3	1.0122	329	0.07
450	1	326.3	319.6	1.0196	320.7	0.11
	2	337.9	329.4	1.0278	331.1	0.17
	3	334.8	326.8	1.124	327.9	0.10
475	1	325.1	316.2	0.9943	317.7	0.15
	2	316.3	308.9	0.9845	310.9	0.20
	3	316.1	307.1	1.0114	310.5	0.34
500	1	320.4	312.9	1.0076	313.9	0.10
	2	330.8	322.6	1.0554	324.1	0.14
	3	320.9	312.5	1.0072	314.6	0.21

Operating temperature (°C)	Iteration No.	Sample #2				
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of the oil (g)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
425	1	337.4	330.3	1	331.2	0.09
	2	339.1	332	1.0021	333.5	0.15
	3	333.9	326.8	1.0152	327.7	0.09
450	1	334.6	327.8	1.0068	329	0.12
	2	334.9	328	1.0367	329.9	0.18
	3	341.5	333.8	0.9918	334.9	0.11
475	1	321.1	311.5	1.0259	313.4	0.19
	2	323.4	315.9	1.0059	318.3	0.24
	3	317.4	307.6	1.0048	311.4	0.38
500	1	317.7	310.4	1.0064	311.8	0.14
	2	317.9	311.2	1.0219	312.8	0.16
	3	325.4	317.7	1.0187	320.1	0.24

Operating temperature (°C)	Iteration No.	Sample #3				
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of the oil (g)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
425	1	340.1	331.7	1.0056	332.5	0.08
	2	323.7	315.8	1.0372	317.1	0.13
	3	325.3	317.2	0.9921	318.3	0.11
450	1	324.9	317.8	0.9984	319.1	0.13
	2	326.3	319.6	1.0372	321.5	0.18
	3	326.9	318.5	1.0011	319.7	0.12
475	1	319.5	311.7	1.0233	313.7	0.20
	2	332.8	325.5	1.0189	327.9	0.24
	3	335.6	327.4	1.0034	330.9	0.35
500	1	329.7	321.6	1.0097	323.1	0.15
	2	334.8	328.9	1.0172	330.7	0.18
	3	329.1	320.5	1.0084	323.1	0.26

SAS code for solid content of poultry litter bio-oil:

```
data PL;
input temp Solid;
datalines;
425    0.08699855
425    0.129121971
425    0.069156293
450    0.107885445
450    0.165401829
450    0.097864769
475    0.150859901
475    0.203148807
475    0.336167688
500    0.099245732
500    0.142126208
500    0.208498809
425    0.09
425    0.14968566
425    0.088652482
450    0.119189511
450    0.18327385
450    0.110909458
475    0.185203236
475    0.238592305
475    0.378184713
500    0.139109698
500    0.156571093
500    0.235594385
425    0.079554495
425    0.125337447
```

```
425   0.11087592
450   0.130208333
450   0.183185499
450   0.119868145
475   0.195446106
475   0.23554814
475   0.348814032
500   0.148558978
500   0.176956351
500   0.257834193
;
run;
proc anova data=PL;
class temp;
model Solid=temp;
means temp/ alpha=0.05;
run;
```

SAS result for solid content of poultry litter bio-oil:

```
                                  The ANOVA Procedure

                         Level of           ------------Solid------------
                         temp         N             Mean          Std Dev

                         425          9       0.10326476       0.02680544
                         450          9       0.13530965       0.03311363
                         475          9       0.25244055       0.08147418
                         500          9       0.17383283       0.05098184


Dependent Variable: Solid

                                            Sum of
      Source                      DF       Squares     Mean Square    F Value    Pr > F

      Model                        3    0.11169675      0.03723225      13.48    <.0001

      Error                       32    0.08841787      0.00276306

      Corrected Total             35    0.20011462


                        R-Square     Coeff Var      Root MSE    Solid Mean

                        0.558164      31.62516      0.052565      0.166212


      Source                      DF      Anova SS     Mean Square    F Value    Pr > F

      temp                         3    0.11169675      0.03723225      13.48    <.0001
```

B.3 VISCOSITY ANALYSIS OF DIFFERENT BIO-OILS

Table B.3.1. Data (pine wood) for Figure 27

Shear Stress (Pa)	Shear Rate (1/s)	Viscosity (Pas)	Log(Viscosity)
0.015	0.0340	0.43	-0.36362
0.362	2.0841	0.17	-0.76025
0.367	5.095	0.07	-1.14256
0.319	8.1708	0.04	-1.40843
0.319	9.7832	0.03	-1.48721
0.387	13.439	0.03	-1.54103
0.450	16.448	0.03	-1.56246
0.516	19.5	0.03	-1.57756
0.531	23.134	0.02	-1.63926
0.516	23.52	0.02	-1.65849
0.609	26.849	0.02	-1.64459
0.725	29.129	0.02	-1.60371
0.913	33.352	0.03	-1.56244
0.995	36.298	0.03	-1.56201
1.119	39.074	0.03	-1.54307
1.213	42.084	0.03	-1.54043
1.283	45.553	0.03	-1.55032
1.279	49.915	0.03	-1.59147
1.295	52.836	0.02	-1.61055
1.349	54.639	0.02	-1.60757
1.379	58.139	0.02	-1.62498
1.373	62.19	0.02	-1.6562
1.124	66.168	0.02	-1.76991
1.138	65.935	0.02	-1.76311
0.575	71.15	0.01	-2.09272
0.494	70.757	0.01	-2.15614
0.456	76.188	0.01	-2.22304
0.402	78.542	0.01	-2.29059
0.418	80.155	0.01	-2.28311
0.444	82.706	0.01	-2.2697
0.454	85.735	0.01	-2.27632
0.480	89.052	0.01	-2.26806
0.492	92.196	0.01	-2.27289
0.499	95.309	0.01	-2.28091
0.514	98.154	0.01	-2.28116

Table B.3.2. Data (underutilized forest) for Figure 27

Shear Stress (Pa)	Shear Rate (1/s)	Viscosity (Pas)	Log(Viscosity)
0.019	0.03	0.62	-0.20653
0.033	0.05	0.70	-0.15531
1.102	4.97	0.22	-0.65412
0.948	9.36	0.10	-0.9943
0.482	13.82	0.03	-1.45724
0.335	15.09	0.02	-1.6538
0.188	20.45	0.01	-2.03704
0.298	21.04	0.01	-1.84921
0.306	26.13	0.01	-1.93078
0.321	30.24	0.01	-1.97359
0.335	33.96	0.01	-2.00569
0.352	36.30	0.01	-2.0138
0.361	39.91	0.01	-2.0431
0.366	43.90	0.01	-2.07899
0.368	46.97	0.01	-2.10623
0.380	50.26	0.01	-2.12125
0.377	53.63	0.01	-2.15303
0.394	55.91	0.01	-2.15229
0.432	59.35	0.01	-2.1381
0.457	63.12	0.01	-2.14035
0.464	67.09	0.01	-2.16038
0.482	70.82	0.01	-2.16692
0.479	74.76	0.01	-2.19312
0.496	78.11	0.01	-2.19714
0.521	81.58	0.01	-2.19518
0.541	85.12	0.01	-2.19695
0.552	88.28	0.01	-2.20391
0.573	91.47	0.01	-2.20283
0.611	94.57	0.01	-2.18936
0.658	97.55	0.01	-2.17098

Table B.3.3. Data (poultry litter) for Figure 27

Shear Stress (Pa)	Shear Rate (1/s)	Viscosity (Pas)	Log(Viscosity)
0.066801	0.065899	1.01	0.005909
1.8709	2.4265	0.77	-0.11293
3.9604	5.7852	0.68	-0.16458
5.3348	9.0836	0.59	-0.23114
7.2125	12.571	0.57	-0.24128
8.0672	16.107	0.50	-0.30029
9.115	19.335	0.47	-0.32657
10.497	21.791	0.48	-0.31721
12.041	23.185	0.52	-0.28453
12.593	29.543	0.43	-0.37034
14.738	30.119	0.49	-0.31039
18.299	32.821	0.56	-0.25372
15.119	35.193	0.43	-0.36693
18.005	40.734	0.44	-0.35456
23.726	47.801	0.50	-0.30422
21.69	47.983	0.45	-0.34483
23.281	55.616	0.42	-0.3782
23.436	55.618	0.42	-0.37534
30.551	54.263	0.56	-0.24948
29.831	55.723	0.54	-0.27137
31.013	60.266	0.51	-0.28853
38.874	83.081	0.47	-0.32984
32.664	73.018	0.45	-0.34936
34.894	74.348	0.47	-0.32851
40.408	79.197	0.51	-0.29223
39.826	85.509	0.47	-0.33185
49.933	95.485	0.52	-0.28155
44.155	90.81	0.49	-0.31315
41.03	88.02	0.47	-0.33147
34.465	90.31	0.38	-0.41836

B.4 EFFECT OF TEMPERATURE ON PHYSICAL PROPERTIES OF BIO-CHAR

Table B.4.1. Data for higher heating value of pine wood bio-char (refer Table 11).

Operating temperature (°C)	Iteration No.	Weight of the sample #1	Energy required (J/g)	Weight of the sample #2	Energy required (J/g)	Weight of the sample #3	Energy required (J/g)
425	1	0.51	24978	0.6011	25067	0.5543	25004
	2	0.4672	26727	0.5281	26644	0.5804	26675
	3	0.5672	26138	0.628	26286	0.4996	26228
450	1	0.6291	25655	0.6361	25692	0.6468	25711
	2	0.5123	27444	0.4337	27561	0.6305	27602
	3	0.5976	27208	0.6	27175	0.5308	27222
475	1	0.4573	28302	0.4898	28248	0.5196	28397
	2	0.538	29061	0.574	29319	0.4783	29168
	3	0.4331	29497	0.5386	29736	0.5338	29641
500	1	0.4819	30234	0.4862	30191	0.6028	30124
	2	0.6459	30239	0.5521	30248	0.5696	30272
	3	0.513	30901	0.5189	30862	0.6452	31007

SAS code for higher heating value of pine wood bio-char:

```
data pinewood;
input temp hhv;
datalines;
425   24978
425   26727
425   26138
450   25655
450   27444
450   27208
475   28302
475   29061
475   29497
500   30234
500   30239
500   30901
425   25067
425   26644
425   26286
450   25692
450   27561
450   27175
475   28248
475   29319
475   29736
500   30191
500   30248
500   30862
```

```
425   25004
425   26675
425   26228
450   25711
450   27602
450   27222
475   28397
475   29168
475   29641
500   30124
500   30272
500   31007
;
run;
proc anova data=pinewood;
class temp;
model hhv=temp;
means temp/ alpha=0.05;
run;
```

SAS result for higher heating value of pine wood bio-char:

```
                                 The ANOVA Procedure

                        Level of          -------------hhv-------------
                        temp        N             Mean          Std Dev

                        425         9       25971.8889       745.954999
                        450         9       26807.7778       854.861067
                        475         9       29041.0000       584.645192
                        500         9       30453.1111       357.128984
Dependent Variable: hhv
                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        3     113555925.6      37851975.2      86.19    <.0001

      Error                       32      14052699.3        439146.9

      Corrected Total             35     127608624.9

                       R-Square     Coeff Var      Root MSE      hhv Mean

                       0.889877      2.360949      662.6816      28068.44

      Source                      DF        Anova SS     Mean Square    F Value    Pr > F

      temp                         3     113555925.6      37851975.2      86.19    <.0001
```

Table B.4.2. Data for ash content of pine wood bio-char (refer Table 11).

Temp (°C)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	15.4949	15.4951	18.2091	2.714	15.5093	0.0142	0.5232
	2	14.4292	14.4297	15.7486	1.3189	14.4401	0.0104	0.7885
	3	14.7352	14.7352	16.5667	1.8315	14.7491	0.0139	0.7589
450	1	14.9327	14.9331	17.1511	2.218	14.953	0.0199	0.8972
	2	14.9745	14.9746	17.2113	2.2367	15.0058	0.0312	1.3949
	3	14.362	14.3628	16.4004	2.0376	14.3853	0.0225	1.1042
475	1	15.1751	15.1763	17.0131	1.8368	15.197	0.0207	1.1270
	2	14.1264	14.1269	16.1406	2.0137	14.141	0.0141	0.7002
	3	14.2175	14.2175	16.1807	1.9632	14.2327	0.0152	0.7742
500	1	14.2744	14.2744	16.8481	2.5737	14.2828	0.0084	0.3264
	2	14.4946	14.4949	16.1933	1.6984	14.508	0.0131	0.7713
	3	14.8899	14.89	16.2675	1.3775	14.896	0.006	0.4356

Temp (°C)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	14.7482	14.7485	17.1294	2.3809	14.7617	0.0132	0.5544
	2	13.7254	13.7258	15.6068	1.881	13.7399	0.0141	0.7496
	3	15.3545	15.3546	16.9991	1.6445	15.3693	0.0147	0.8939
450	1	13.9845	12.9851	15.3655	2.3804	13.005	0.0199	0.8360
	2	12.897	12.897	15.232	2.335	12.9289	0.0319	1.3662
	3	15.1174	15.1176	17.2375	2.1199	15.1413	0.0237	1.1180
475	1	14.3482	14.3482	16.4064	2.0582	14.3712	0.023	1.1175
	2	15.0009	15.0019	17.1138	2.1119	15.017	0.0151	0.7150
	3	15.138	15.1381	16.8731	1.735	15.1536	0.0155	0.8934
500	1	14.5028	14.5033	16.7285	2.2252	14.5095	0.0062	0.2786
	2	14.6681	14.6683	16.3004	1.6321	14.6815	0.0132	0.8088
	3	15.4717	15.4719	17.0858	1.6139	15.4792	0.0073	0.4523

Temp (°C)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	15.4949	15.4951	18.2178	2.7227	15.5088	0.0137	0.5032
	2	14.4292	14.4297	15.7961	1.3664	14.4397	0.01	0.7319
	3	14.7352	14.7352	16.4589	1.7237	14.7484	0.0132	0.7658
450	1	14.9327	14.9331	17.1695	2.2364	14.9538	0.0207	0.9256
	2	14.9745	14.9746	17.8792	2.9046	15.0157	0.0411	1.4150
	3	14.362	14.3628	16.1259	1.7631	14.3825	0.0197	1.1174
475	1	15.1751	15.1763	17.6597	2.4834	15.2038	0.0275	1.1074
	2	14.1264	14.1269	16.568	2.4411	14.1445	0.0176	0.7210
	3	14.2175	14.2175	16.14	1.9225	14.233	0.0155	0.8062
500	1	14.2744	14.2744	16.1294	1.855	14.2798	0.0054	0.2911
	2	14.4946	14.4949	16.2369	1.742	14.5085	0.0136	0.7807
	3	14.8899	14.89	16.7456	1.8556	14.8977	0.0077	0.4150

SAS code for ash content of pine wood bio-char:

```
data pinewood;
input temp Ash;
datalines;
425   0.52321297
425   0.788535901
425   0.758940759
450   0.897204689
450   1.394912147
450   1.104240283
475   1.12695993
475   0.700203605
475   0.774246129
500   0.326378366
500   0.771314178
500   0.435571688
425   0.554412197
425   0.749601276
425   0.89388872
450   0.835993951
450   1.366167024
450   1.117977263
475   1.117481294
475   0.714995975
475   0.893371758
500   0.27862664
500   0.808773972
500   0.452320466
425   0.503176993
```

```
425   0.731850117
425   0.765794512
450   0.925594706
450   1.414996901
450   1.117350122
475   1.107352823
475   0.720986441
475   0.806241873
500   0.291105121
500   0.780711825
500   0.414960121
;
run;
proc anova data=pinewood;
class temp;
model Ash=temp;
means temp/ alpha=0.05;
run;
```

SAS result for ash content of pine wood bio-char:

```
                               The ANOVA Procedure

              Level of          -------------Ash-------------
              temp         N             Mean          Std Dev

              425          9       0.69660149       0.13591997
              450          9       1.13049301       0.22095170
              475          9       0.88464887       0.18388947
              500          9       0.50664026       0.21903164
Dependent Variable: Ash
                                        Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        3      1.91751981      0.63917327      17.15    <.0001

      Error                       32      1.19267269      0.03727102

      Corrected Total             35      3.11019250

                 R-Square     Coeff Var      Root MSE      Ash Mean
                 0.616528      23.99429      0.193057      0.804596

      Source                      DF        Anova SS     Mean Square    F Value    Pr > F
      temp                         3      1.91751981      0.63917327      17.15    <.0001
```

Table B.4.3. Data for moisture content of pine wood bio-char (refer Table 11).

Temp (°C)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
425	1	46.6343	50.6475	4.0132	50.5321	3.8978	0.1154	2.88
	2	42.3064	44.9326	2.6262	44.86	2.5536	0.0726	2.76
	3	42.412	44.935	2.523	44.869	2.457	0.066	2.62
450	1	46.9118	50.771	3.8592	50.6587	3.7469	0.1123	2.91
	2	48.7604	52.1998	3.4394	52.0891	3.3287	0.1107	3.22
	3	46.5236	50.0761	3.5525	49.9696	3.446	0.1065	3.00
475	1	46.7121	50.1644	3.4523	50.0623	3.3502	0.1021	2.96
	2	47.0303	49.8158	2.7855	49.7345	2.7042	0.0813	2.92
	3	48.5496	50.5131	1.9635	50.4455	1.8959	0.0676	3.44
500	1	96.9211	100.3934	3.4723	100.2735	3.3524	0.1199	3.45
	2	93.5845	97.114	3.5295	96.969	3.3845	0.145	4.11
	3	152.4772	156.1768	3.6996	156.0545	3.5773	0.1223	3.31

Temp (°C)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
425	1	45.8667	49.5468	3.6801	49.4419	3.5752	0.1049	2.85
	2	46.749	50.1036	3.3546	50.0079	3.2589	0.0957	2.85
	3	46.3932	49.3896	2.9964	49.31	2.9168	0.0796	2.66
450	1	46.0832	51.2258	5.1426	51.0687	4.9855	0.1571	3.05
	2	47.8766	52.5363	4.6597	52.3881	4.5115	0.1482	3.18
	3	48.1352	52.8214	4.6862	52.6635	4.5283	0.1579	3.37
475	1	47.4912	52.4574	4.9662	52.311	4.8198	0.1464	2.95
	2	47.3427	50.9786	3.6359	50.8711	3.5284	0.1075	2.96
	3	103.75	109.6048	5.8548	109.3555	5.6055	0.2493	4.26
500	1	92.085	95.7132	3.6282	95.5872	3.5022	0.126	3.47
	2	113.0288	116.7161	3.6873	116.5723	3.5435	0.1438	3.90
	3	121.4935	125.0328	3.5393	124.9066	3.4131	0.1262	3.57

Temp (°C)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
425	1	46.6343	50.268	3.6337	50.1665	3.5322	0.1015	2.79
	2	42.3064	45.0459	2.7395	44.9709	2.6645	0.075	2.74
	3	42.412	44.8569	2.4449	44.7902	2.3782	0.0667	2.73
450	1	46.9118	50.1267	3.2149	50.0226	3.1108	0.1041	3.24
	2	48.7604	52.4875	3.7271	52.3754	3.615	0.1121	3.01
	3	46.5236	50.7593	4.2357	50.6203	4.0967	0.139	3.28
475	1	46.7121	50.1251	3.413	50.0202	3.3081	0.1049	3.07
	2	47.0303	49.7766	2.7463	49.6894	2.6591	0.0872	3.18
	3	48.5496	50.9981	2.4485	50.8989	2.3493	0.0992	4.05
500	1	96.9211	100.1032	3.1821	99.9874	3.0663	0.1158	3.64
	2	93.5845	97.2567	3.6722	97.1168	3.5323	0.1399	3.81
	3	152.4772	155.8759	3.3987	155.7569	3.2797	0.119	3.50

SAS code for moisture content of pine wood bio-char:

```
data pinewood;
input temp Moisture;
datalines;
425    2.875510814
425    2.764450537
425    2.615933413
450    2.909929519
450    3.218584637
450    2.997888811
475    2.957448657
475    2.918686053
475    3.442831678
500    3.453042652
500    4.108230628
500    3.305762785
425    2.85046602
425    2.852799141
425    2.656521159
450    3.054874966
450    3.180462262
450    3.369467799
475    2.947927993
475    2.95662697
475    4.258044681
500    3.472796428
500    3.899872535
500    3.565676829
425    2.793296089
425    2.737725862
425    2.72812794
450    3.23804784
450    3.007700357
450    3.281629955
475    3.073542338
475    3.175181153
475    4.051460078
500    3.639106251
500    3.809705354
500    3.501338747
;
run;
proc anova data=pinewood;
class temp;
model Moisture=temp;
means temp/ alpha=0.05;
run;
```

SAS result for moisture content of pine wood bio-char:

```
                          The ANOVA Procedure

            Level of          -----------Moisture----------
            temp        N             Mean           Std Dev
```

```
                    425          9       2.76387011       0.08951758
                    450          9       3.13984291       0.15330439
                    475          9       3.30908329       0.50912480
                    500          9       3.63950358       0.25370939

Dependent Variable: Moisture

                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        3      3.58386209      1.19462070      13.46    <.0001

      Error                       32      2.84073719      0.08877304

      Corrected Total             35      6.42459928


                    R-Square     Coeff Var      Root MSE    Moisture Mean

                    0.557834      9.272988      0.297948         3.213075

      Source                      DF        Anova SS     Mean Square    F Value    Pr > F

      temp                         3      3.58386209      1.19462070      13.46    <.0001
```

Table B.4.4. Data for higher heating value of underutilized forest bio-char (refer Table 12).

Operating temperature (°C)	Iteration No.	Weight of the sample #1	Energy required (J/g)	Weight of the sample #2	Energy required (J/g)	Weight of the sample #3	Energy required (J/g)
425	1	0.5791	22714	0.5237	23409	0.5391	23012
	2	0.4841	22581	0.6017	22286	0.5296	22379
	3	0.5211	23599	0.5218	24075	0.5473	23702
450	1	0.6137	23784	0.5004	23540	0.5321	23581
	2	0.5229	24736	0.5458	24642	0.5047	24698
	3	0.6481	22079	0.6459	22820	0.5219	23002
475	1	0.5222	23066	0.497	23490	0.5478	23545
	2	0.5491	23684	0.6125	23733	0.5189	23789
	3	0.5164	24203	0.5746	24573	0.5694	24612
500	1	0.5421	25037	0.5479	26437	0.5517	26359
	2	0.5318	25820	0.5678	26418	0.5684	26138
	3	0.5418	25957	0.5765	25463	0.5501	25879

SAS code for higher heating value of underutilized forest bio-char:

```
data UU;
input temp HHV;
datalines;
425   22714
```

```
425   22581
425   23599
450   23784
450   24736
450   22079
475   23066
475   23684
475   24203
500   25037
500   25820
500   25957
425   23409
425   22286
425   24075
450   23540
450   24642
450   22820
475   23490
475   23733
475   24573
500   26437
500   26418
500   25463
425   23012
425   22379
425   23702
450   23581
450   24698
450   23002
475   23545
475   23789
475   24612
500   26359
500   26138
500   25879
;
run;
proc anova data=UU;
class temp;
model HHV=temp;
means temp/ alpha=0.05;
run;
```

SAS result for higher heating value of underutilized forest bio-char:

The ANOVA Procedure

Level of temp	N	HHV Mean	HHV Std Dev
425	9	23084.1111	638.726946
450	9	23653.5556	926.911014
475	9	23855.0000	513.566451
500	9	25945.3333	467.887540

Dependent Variable: HHV

```
                                        Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        3     42226757.89     14075585.96      32.18    <.0001

Error                       32     13998443.11       437451.35

Corrected Total             35     56225201.00

                 R-Square     Coeff Var      Root MSE      HHV Mean
                 0.751029      2.740480      661.4010      24134.50

Source                      DF         Anova SS    Mean Square    F Value    Pr > F
temp                         3     42226757.89     14075585.96      32.18    <.0001
```

Table B.4.5. Data for ash content of underutilized forest bio-char (refer Table 12).

Temp (°C)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	18.1379	18.1366	18.7185	0.5819	18.15	0.0134	2.3028
	2	18.378	18.3767	19.1072	0.7305	18.3897	0.013	1.7796
	3	17.7647	17.7631	18.3831	0.62	17.7747	0.0116	1.8710
450	1	18.378	18.3767	20.1493	1.7726	18.4152	0.0385	2.1720
	2	17.7647	17.7631	18.9527	1.1896	17.7981	0.035	2.9422
	3	18.1379	18.1366	19.5595	1.4229	18.1789	0.0423	2.9728
475	1	17.7647	17.7631	19.1354	1.3723	17.7948	0.0317	2.3100
	2	18.1379	18.1366	19.8946	1.758	18.1828	0.0462	2.6280
	3	18.378	18.3767	19.7203	1.3436	18.4326	0.0559	4.1605
500	1	18.1379	18.1366	19.5285	1.3919	18.1796	0.043	3.0893
	2	18.378	18.3767	20.0342	1.6575	18.4251	0.0484	2.9201
	3	17.7647	17.7631	19.4099	1.6468	17.839	0.0759	4.6089

Temp (°C)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	17.9566	17.9555	18.7767	0.8212	17.9727	0.0172	2.0945
	2	18.1617	18.1607	18.8907	0.73	18.1765	0.0158	2.1644
	3	17.4236	17.4225	18.1149	0.6924	17.434	0.0115	1.6609
450	1	18.1617	18.1607	19.7392	1.5785	18.1908	0.0301	1.9069
	2	17.4236	17.4225	18.6076	1.1851	17.4581	0.0356	3.0040
	3	17.9566	17.9555	18.9934	1.0379	17.987	0.0315	3.0350
475	1	17.4236	17.4225	18.637	1.2145	17.4512	0.0287	2.3631
	2	17.9566	17.9555	19.1465	1.191	17.9866	0.0311	2.6113
	3	18.1617	18.1607	19.3858	1.2251	18.2064	0.0457	3.7303
500	1	17.9566	17.9555	18.9746	1.0191	17.9856	0.0301	2.9536
	2	18.1617	18.1607	19.1159	0.9552	18.1857	0.025	2.6173
	3	17.4236	17.4225	18.5961	1.1736	17.4708	0.0483	4.1155

Temp (°C)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	17.828	17.8266	18.3376	0.511	17.8374	0.0108	2.1135
	2	17.4198	17.4187	18.244	0.8253	17.4393	0.0206	2.4961
	3	17.7111	17.7101	18.1612	0.4511	17.7184	0.0083	1.8399
450	1	17.4198	17.4187	18.7105	1.2918	17.4511	0.0324	2.5081
	2	17.7111	17.7101	19.0615	1.3514	17.752	0.0419	3.1005
	3	17.828	17.8266	19.0946	1.268	17.8653	0.0387	3.0521
475	1	17.7111	17.7101	18.7176	1.0075	17.7327	0.0226	2.2432
	2	17.828	17.8266	19.2246	1.398	17.8638	0.0372	2.6609
	3	17.4198	17.4187	18.4442	1.0255	17.4596	0.0409	3.9883
500	1	17.828	17.8266	18.9554	1.1288	17.8599	0.0333	2.9500
	2	17.4198	17.4187	18.6463	1.2276	17.4582	0.0395	3.2177
	3	17.7111	17.7101	19.2567	1.5466	17.7787	0.0686	4.4355

SAS code for ash content of underutilized forest bio-char:

```
data UU;
input temp Ash;
datalines;
425   2.302801169
425   1.779603012
425   1.870967742
450   2.171950807
450   2.942165434
450   2.972802024
475   2.309990527
475   2.627986348
475   4.160464424
500   3.089302392
500   2.920060332
500   4.608938547
425   2.09449586
425   2.164383562
425   1.660889659
450   1.906873614
450   3.00396591
450   3.034974468
475   2.363112392
475   2.61125105
475   3.73030773
500   2.953586498
500   2.617252931
500   4.115541922
425   2.113502935
425   2.496062038
425   1.839946797
450   2.508128193
450   3.100488382
450   3.052050473
475   2.243176179
475   2.660944206
475   3.988298391
500   2.950035436
500   3.217660476
500   4.435536014
;
run;
proc anova data=UU;
class temp;
model Ash=temp;
means temp/ alpha=0.05;
run;
```

SAS result for ash content of underutilized forest bio-char:

```
                          The ANOVA Procedure

              Level of           -------------Ash-------------
              temp          N              Mean           Std Dev
```

425	9	2.03585031	0.26946016
450	9	2.74371103	0.44009985
475	9	2.96617014	0.76693062
500	9	3.43421273	0.74245385

Dependent Variable: Ash

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	9.15147845	3.05049282	8.68	0.0002
Error	32	11.24573559	0.35142924		
Corrected Total	35	20.39721404			

R-Square	Coeff Var	Root MSE	Ash Mean
0.448663	21.20993	0.592815	2.794986

Source	DF	Anova SS	Mean Square	F Value	Pr > F
temp	3	9.15147845	3.05049282	8.68	0.0002

Table B.4.6. Data for moisture content of underutilized forest bio-char (refer Table 12).

Temp (°C)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
425	1	43.5	47.1744	3.6744	47.1197	3.6197	0.0547	1.49
	2	46.139	49.426	3.287	49.378	3.239	0.048	1.46
	3	42.949	46.68	3.731	46.6236	3.6746	0.0564	1.51
450	1	43.2425	46.002	2.7595	45.9668	2.7243	0.0352	1.28
	2	44.0061	46.133	2.1269	46.1153	2.1092	0.0177	0.83
	3	42.118	45.416	3.298	45.3952	3.2772	0.0208	0.63
475	1	46.1815	49.178	2.9965	49.1517	2.9702	0.0263	0.88
	2	45.977	48.4219	2.4449	48.3802	2.4032	0.0417	1.71
	3	44.6883	48.5	3.8117	48.4589	3.7706	0.0411	1.08
500	1	44.637	47.734	3.097	47.6959	3.0589	0.0381	1.23
	2	41.789	44.23	2.441	44.1916	2.4026	0.0384	1.57
	3	48.245	49.749	1.504	49.7406	1.4956	0.0084	0.56

Temp (°C)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
425	1	47.575	50.7848	3.2098	50.7485	3.1735	0.0363	1.13
	2	45.56	48.1153	2.5553	48.1059	2.5459	0.0094	0.37
	3	48.369	50.1177	1.7487	50.1013	1.7323	0.0164	0.94
450	1	43.562	46.843	3.281	46.8343	3.2723	0.0087	0.27
	2	46.8443	48.4127	1.5684	48.4077	1.5634	0.005	0.32
	3	43.1858	44.4948	1.309	44.494	1.3082	0.0008	0.06
475	1	46.945	48.4598	1.5148	48.456	1.511	0.0038	0.25
	2	46.6382	48.1803	1.5421	48.1689	1.5307	0.0114	0.74
	3	45.8689	47.2541	1.3852	47.2466	1.3777	0.0075	0.54
500	1	46.7538	48.0021	1.2483	48.001	1.2472	0.0011	0.09
	2	42.4188	44.5996	2.1808	44.5769	2.1581	0.0227	1.04
	3	46.3995	47.9312	1.5317	47.9282	1.5287	0.003	0.20

Temp (°C)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
425	1	46.916	49.221	2.305	49.1873	2.2713	0.0337	1.46
	2	46.089	48.967	2.878	48.9453	2.8563	0.0217	0.75
	3	48.7639	50.6366	1.8727	50.6154	1.8515	0.0212	1.13
450	1	46.519	47.8638	1.3448	47.85	1.331	0.0138	1.03
	2	48.144	49.7285	1.5845	49.7188	1.5748	0.0097	0.61
	3	46.7168	48.4028	1.686	48.4019	1.6851	0.0009	0.05
475	1	47.0338	48.7202	1.6864	48.7149	1.6811	0.0053	0.31
	2	47.3458	48.73	1.3842	48.7185	1.3727	0.0115	0.83
	3	48.5515	50.059	1.5075	50.05	1.4985	0.009	0.60
500	1	17.712	18.5948	0.8828	18.5914	0.8794	0.0034	0.39
	2	17.5664	18.5081	0.9417	18.496	0.9296	0.0121	1.28
	3	17.8312	18.8985	1.0673	18.8867	1.0555	0.0118	1.11

SAS code for moisture content of underutilized forest bio-char:

```
data UU;
input temp Moisture;
datalines;
425    1.488678424
425    1.460298144
425    1.511659073
450    1.275593405
450    0.832197094
450    0.630685264
475    0.877690639
475    1.705591231
475    1.078259045
500    1.230222796
500    1.573125768
500    0.558510638
425    1.130911583
425    0.367862873
425    0.937839538
450    0.26516306
450    0.318796225
450    0.061115355
475    0.250858199
475    0.73925167
475    0.541438059
500    0.088119843
500    1.040902421
500    0.195860808
425    1.462039046
425    0.75399583
425    1.132055321
450    1.026174896
450    0.612180499
450    0.053380783
475    0.314278937
475    0.830804797
475    0.597014925
500    0.385138197
500    1.284910269
500    1.105593554
;
run;
proc anova data=UU;
class temp;
model Moisture=temp;
means temp/ alpha=0.05;
run;
```

SAS result for moisture content of underutilized forest bio-char:

```
                              The ANOVA Procedure

                Level of          -----------Moisture----------
                temp         N            Mean            Std Dev
```

```
                    425           9         1.13837109        0.39563127
                    450           9         0.56392073        0.42745206
                    475           9         0.77057639        0.43959439
                    500           9         0.82915381        0.53196686

Dependent Variable: Moisture
                                                   Sum of
      Source                        DF            Squares     Mean Square    F Value    Pr > F
      Model                          3         1.52407789      0.50802596       2.49    0.0779
      Error                         32         6.52377066      0.20386783
      Corrected Total               35         8.04784855

                   R-Square     Coeff Var      Root MSE    Moisture Mean
                   0.189377      54.69585      0.451517         0.825506

      Source                        DF           Anova SS     Mean Square    F Value    Pr > F
      temp                           3         1.52407789      0.50802596       2.49    0.0779
```

Table B.4.7. Data for higher heating value of poultry litter bio-char (refer Table 13).

Operating temperature (°C)	Iteration No.	Weight of the sample #1	Energy required (J/g)	Weight of the sample #2	Energy required (J/g)	Weight of the sample #3	Energy required (J/g)
425	1	0.5437	11810	0.5075	11891	0.5623	11789
	2	0.513	12352	0.5568	12615	0.498	12490
	3	0.5028	12118	0.5107	12117	0.5432	12209
450	1	0.4444	11194	0.493	11120	0.5239	11202
	2	0.5128	10668	0.502	10771	0.4927	10758
	3	0.5119	11407	0.5122	11668	0.5421	11661
475	1	0.5371	10978	0.5225	11068	0.4728	11081
	2	0.5088	11445	0.5549	11448	0.5174	11493
	3	0.5607	10646	0.6442	10624	0.5876	10651
500	1	0.5262	10824	0.5415	10829	0.4987	10841
	2	0.5036	11074	0.5315	11239	0.5678	11112
	3	0.5752	10446	0.5763	10483	0.5129	10477

SAS code for higher heating value of poultry litter bio-char:

```
data PL;
input temp HHV;
datalines;
425    11810
425    12352
425    12118
450    11194
450    10668
450    11407
475    10978
475    11445
```

```
475    10646
500    10824
500    11074
500    10446
425    11891
425    12615
425    12117
450    11120
450    10771
450    11668
475    11068
475    11448
475    10624
500    10829
500    11239
500    10483
425    11789
425    12490
425    12209
450    11202
450    10758
450    11661
475    11081
475    11493
475    10651
500    10841
500    11112
500    10477
;
run;
proc anova data=PL;
class temp;
model HHV=temp;
means temp/ alpha=0.05;
run;
```

SAS result for higher heating value of poultry litter bio-char:

The ANOVA Procedure

Level of temp	N	HHV Mean	HHV Std Dev
425	9	12154.5556	293.904368
450	9	11161.0000	375.761560
475	9	11048.2222	357.248435
500	9	10813.8889	295.092547

Dependent Variable: HHV

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	9442418.08	3147472.69	28.47	<.0001
Error	32	3538260.67	110570.65		
Corrected Total	35	12980678.75			

R-Square	Coeff Var	Root MSE	HHV Mean
0.727421	2.944124	332.5216	11294.42

Source	DF	Anova SS	Mean Square	F Value	Pr > F
temp	3	9442418.083	3147472.694	28.47	<.0001

Table B.4.8. Data for ash content of poultry litter bio-char (refer Table 13).

Temp (°C)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	15.4928	15.4918	16.2671	0.7753	15.901	0.4092	52.7796
	2	14.4324	14.4299	15.4451	1.0152	14.842	0.4121	40.5930
	3	14.74	14.7386	15.5342	0.7956	15.1142	0.3756	47.2097
450	1	14.9381	14.9372	16.0048	1.0676	15.5193	0.5821	54.5242
	2	14.9786	14.975	16.2666	1.2916	15.729	0.754	58.3772
	3	14.3689	14.3642	15.5917	1.2275	15.0558	0.6916	56.3422
475	1	15.1845	15.1809	16.5941	1.4132	16.014	0.8331	58.9513
	2	14.1347	14.131	15.241	1.11	14.7944	0.6634	59.7658
	3	14.2151	14.2134	15.5012	1.2878	14.9513	0.7379	57.2993
500	1	14.2743	14.2739	15.8913	1.6174	15.154	0.8801	54.4145
	2	14.4892	14.489	15.8304	1.3414	15.2884	0.7994	59.5945
	3	14.8947	14.8935	16.3717	1.4782	15.784	0.8905	60.2422

Temp (°C)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	14.7423	14.741	15.271	0.53	15.0293	0.2883	54.3962
	2	14.2774	14.2769	14.9274	0.6505	14.5583	0.2814	43.2590
	3	15.3551	15.3547	16.3613	1.0066	15.8305	0.4758	47.2680
450	1	12.9784	12.978	14.3797	1.4017	13.7621	0.7841	55.9392
	2	12.8959	12.8959	14.2424	1.3465	13.6654	0.7695	57.1482
	3	15.1221	15.1214	16.3927	1.2713	15.8389	0.7175	56.4383
475	1	14.3498	14.3487	15.4685	1.1198	14.9702	0.6215	55.5010
	2	15.0069	15.0058	16.3294	1.3236	15.7546	0.7488	56.5730
	3	15.1387	15.138	16.7015	1.5635	16.0175	0.8795	56.2520
500	1	14.5049	14.5036	15.9767	1.4731	15.33	0.8264	56.0994
	2	14.6652	14.6643	16.0283	1.364	15.4794	0.8151	59.7581
	3	15.4697	15.4681	16.9575	1.4894	16.3844	0.9163	61.5214

Temp (°C)	Iteration No.	Sample #3						
		Weight of crusible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
425	1	15.4928	15.4918	16.4126	0.9208	15.989	0.4972	53.9965
	2	14.4324	14.4299	15.4879	1.058	14.8875	0.4576	43.2514
	3	14.74	14.7386	15.689	0.9504	15.1878	0.4492	47.2643
450	1	14.9381	14.9372	15.7536	0.8164	15.3938	0.4566	55.9285
	2	14.9786	14.975	15.8549	0.8799	15.4778	0.5028	57.1429
	3	14.3689	14.3642	14.9663	0.6021	14.704	0.3398	56.4358
475	1	15.1845	15.1809	15.8697	0.6888	15.5831	0.4022	58.3914
	2	14.1347	14.131	15.6589	1.5279	15.0153	0.8843	57.8768
	3	14.2151	14.2134	14.7416	0.5282	14.5115	0.2981	56.4370
500	1	14.2743	14.2739	15.0015	0.7276	14.683	0.4091	56.2259
	2	14.4892	14.489	15.1256	0.6366	14.869	0.38	59.6921
	3	14.8947	14.8935	15.4569	0.5634	15.2391	0.3456	61.3419

SAS code for ash content of poultry litter bio-char:

```
data PL;
input temp Ash;
datalines;
425   52.7795692
425   40.5929866
425   47.20965309
450   54.52416635
450   58.37720657
450   56.34215886
475   58.95131616
475   59.76576577
475   57.29927007
500   54.4144924
500   59.59445356
500   60.24218644
425   54.39622642
425   43.25903151
425   47.268031
450   55.93921667
450   57.1481619
450   56.43829151
475   55.50098232
475   56.57298277
475   56.25199872
500   56.09938226
500   59.75806452
500   61.52141802
425   53.99652476
```

```
425   43.25141777
425   47.26430976
450   55.92846644
450   57.14285714
450   56.43580801
475   58.39140534
475   57.8768244
475   56.4369557
500   56.22594832
500   59.69211436
500   61.34185304
;
run;
proc anova data=PL;
class temp;
model Ash=temp;
means temp/ alpha=0.05;
run;
```

SAS result for ash content of poultry litter bio-char:

```
                              The ANOVA Procedure

                    Level of          -------------Ash-------------
                    temp         N            Mean          Std Dev

                    425          9      47.7797500       5.01085126
                    450          9      56.4751482       1.05650454
                    475          9      57.4497224       1.40254938
                    500          9      58.7655459       2.53557237

Dependent Variable: Ash

                                        Sum of
      Source                     DF        Squares     Mean Square    F Value    Pr > F

      Model                       3    669.8995496     223.2998499      25.80    <.0001

      Error                      32    276.9688337       8.6552761

      Corrected Total            35    946.8683833


                   R-Square     Coeff Var      Root MSE      Ash Mean

                   0.707490      5.337657      2.941985      55.11754


      Source                     DF       Anova SS     Mean Square    F Value    Pr > F

      temp                        3    669.8995496     223.2998499      25.80    <.0001
```

Table B.4.9. Data for moisture content of poultry litter bio-char (refer Table 13).

Temp (°C)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
425	1	43.4951	47.236	3.7409	47.0863	3.5912	0.1497	4.00
	2	42.9424	46.8331	3.8907	46.715	3.7726	0.1181	3.04
	3	43.2417	46.9396	3.6979	46.8485	3.6068	0.0911	2.46
450	1	42.1114	45.2703	3.1589	45.1504	3.039	0.1199	3.80
	2	46.1775	49.5704	3.3929	49.4795	3.302	0.0909	2.68
	3	44.6864	49.0111	4.3247	48.9426	4.2562	0.0685	1.58
475	1	44.36	48.0972	3.7372	47.939	3.579	0.1582	4.23
	2	48.2386	52.4554	4.2168	52.3167	4.0781	0.1387	3.29
	3	45.5597	49.866	4.3063	49.7743	4.2146	0.0917	2.13
500	1	47.5009	51.7488	4.2479	51.5616	4.0607	0.1872	4.41
	2	46.8336	51.2526	4.419	51.0802	4.2466	0.1724	3.90
	3	46.0423	50.1707	4.1284	50.0563	4.014	0.1144	2.77

Temp (°C)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
425	1	46.1278	49.4853	3.3575	49.3557	3.2279	0.1296	3.86
	2	45.4166	49.783	4.3664	49.6526	4.236	0.1304	2.99
	3	44.0149	47.7219	3.707	47.6341	3.6192	0.0878	2.37
450	1	45.7667	50.4866	4.7199	50.3067	4.54	0.1799	3.81
	2	45.9833	51.0141	5.0308	50.9034	4.9201	0.1107	2.20
	3	46.7795	52.8452	6.0657	52.7523	5.9728	0.0929	1.53
475	1	41.791	46.6566	4.8656	46.4372	4.6462	0.2194	4.51
	2	47.5682	51.6919	4.1237	51.548	3.9798	0.1439	3.49
	3	48.3674	53.708	5.3406	53.5847	5.2173	0.1233	2.31
500	1	45.5664	49.2776	3.7112	49.1078	3.5414	0.1698	4.58
	2	43.1856	47.2647	4.0791	47.112	3.9264	0.1527	3.74
	3	46.941	51.5296	4.5886	51.4022	4.4612	0.1274	2.78

Temp (°C)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
425	1	43.4951	47.2456	3.7505	47.0983	3.6032	0.1473	3.93
	2	42.9424	46.8789	3.9365	46.7616	3.8192	0.1173	2.98
	3	43.2417	46.9127	3.671	46.8204	3.5787	0.0923	2.51
450	1	42.1114	45.2002	3.0888	45.0844	2.973	0.1158	3.75
	2	46.1775	49.4589	3.2814	49.3701	3.1926	0.0888	2.71
	3	44.6864	49.0457	4.3593	48.9826	4.2962	0.0631	1.45
475	1	44.36	48.0168	3.6568	47.8591	3.4991	0.1577	4.31
	2	48.2386	52.4023	4.1637	52.2767	4.0381	0.1256	3.02
	3	45.5597	49.8455	4.2858	49.7543	4.1946	0.0912	2.13
500	1	47.5009	51.7969	4.296	51.5998	4.0989	0.1971	4.59
	2	46.8336	51.2003	4.3667	51.0411	4.2075	0.1592	3.65
	3	46.0423	50.1189	4.0766	50.0048	3.9625	0.1141	2.80

SAS code for moisture content of poultry litter bio-char:

```
data PL;
input temp Moisture;
datalines;
425    4.001710818
425    3.035443493
425    2.463560399
450    3.795625059
450    2.679124053
450    1.583924897
475    4.233115702
475    3.289224056
475    2.129438265
500    4.406883401
500    3.901335144
500    2.771049317
425    3.860014892
425    2.98644192
425    2.368492042
450    3.811521431
450    2.200445257
450    1.531562722
475    4.509207498
475    3.489584596
475    2.308729356
500    4.575339513
500    3.743472825
500    2.776445975
425    3.927476336
425    2.979804395
425    2.51430128
450    3.749028749
450    2.706162004
450    1.4474801
475    4.312513673
475    3.016547782
475    2.127957441
500    4.587988827
500    3.645773696
500    2.798901045
;
run;
proc anova data=PL;
class temp;
model Moisture=temp;
means temp/ alpha=0.05;
run;
```

SAS result for moisture content of poultry litter bio-char:

```
                          The ANOVA Procedure

                    Level of          -----------Moisture----------
                    temp         N              Mean           Std Dev
```

425	9	3.12636062	0.65037301
450	9	2.61165270	0.99346568
475	9	3.26847982	0.94815937
500	9	3.68968775	0.76048648

Dependent Variable: Moisture

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	5.34027854	1.78009285	2.47	0.0801
Error	32	23.09843977	0.72182624		
Corrected Total	35	28.43871831			

R-Square	Coeff Var	Root MSE	Moisture Mean
0.187782	26.76722	0.849604	3.174045

Source	DF	Anova SS	Mean Square	F Value	Pr > F
temp	3	5.34027854	1.78009285	2.47	0.0801

B.5 MULTIPLE COMPARISON

This section comprises of all the data and results (from Minitab software) required to interpret the multiple comparison analysis between the effect of different types of biomass and operating temperatures over the yield of various products of the pyrolysis process, and the physical properties of bio-oil and biochar.

Minitab worksheet for bio-oil production:

Biomass Type	Temp	Oil Yield
PW	425	30
PW	425	29.6
PW	425	29
PW	450	30
PW	450	32.2
PW	450	33.4
PW	475	36.2
PW	475	34.6
PW	475	35.8
PW	500	37.6
PW	500	36.4
PW	500	39.4
UU	425	30.4
UU	425	29.6
UU	425	31.2
UU	450	31.8
UU	450	35
UU	450	30.8
UU	475	32
UU	475	32
UU	475	31.2
UU	500	34.2
UU	500	32.8
UU	500	31.4
PL	425	32.2
PL	425	32.8
PL	425	33
PL	450	33.4
PL	450	33.6
PL	450	32.8

Biomass Type	Temp	Oil Yield
PL	475	35.4
PL	475	34.4
PL	475	34.6
PL	500	31.2
PL	500	29.4
PL	500	26

Minitab result for bio-oil production:

Two-way ANOVA: Oil Yield versus Biomass Type, Temp

```
Source        DF       SS       MS      F      P
Biomass Type   2   20.927  10.4633   5.86  0.008
Temp           3   47.950  15.9833   8.95  0.000
Interaction    6  142.380  23.7300  13.29  0.000
Error         24   42.853   1.7856
Total         35  254.110

S = 1.336   R-Sq = 83.14%   R-Sq(adj) = 75.41%


                    Individual 95% CIs For Mean Based on
Biomass             Pooled StDev
Type         Mean   ---------+---------+---------+---------+
PL        32.4000        (-------*-------)
PW        33.6833                     (-------*-------)
UU        31.8667   (-------*-------)
                    ---------+---------+---------+---------+
                          32.0      33.0      34.0      35.0


                 Individual 95% CIs For Mean Based on Pooled StDev
Temp     Mean       +---------+---------+---------+---------
425   30.8667       (-----*-----)
450   32.5556                  (-----*-----)
475   34.0222                            (-----*-----)
500   33.1556                      (-----*-----)
                    +---------+---------+---------+---------
                 30.0      31.5      33.0      34.5
```

General Linear Model: Oil Yield versus Biomass Type, Temp

```
Factor        Type   Levels  Values
Biomass Type  fixed       3  PL, PW, UU
Temp          fixed       4  425, 450, 475, 500


Analysis of Variance for Oil Yield, using Adjusted SS for Tests

Source             DF   Seq SS   Adj SS  Adj MS      F      P
Biomass Type        2   20.927   20.927  10.463   5.86  0.008
Temp                3   47.950   47.950  15.983   8.95  0.000
Biomass Type*Temp   6  142.380  142.380  23.730  13.29  0.000
Error              24   42.853   42.853   1.786
```

```
Total              35  254.110


S = 1.33625   R-Sq = 83.14%   R-Sq(adj) = 75.41%


Unusual Observations for Oil Yield

Obs  Oil Yield      Fit  SE Fit  Residual  St Resid
 17    35.0000  32.5333  0.7715    2.4667      2.26 R
 34    31.2000  28.8667  0.7715    2.3333      2.14 R
 36    26.0000  28.8667  0.7715   -2.8667     -2.63 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Oil Yield
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass
Type      Lower   Center   Upper     +---------+---------+---------+------
PW       -0.078   1.2833  2.6450                         (-------*--------)
UU       -1.895  -0.5333  0.8283             (--------*-------)
                                     +---------+---------+---------+------
                                  -3.2      -1.6       0.0       1.6


Biomass Type = PW  subtracted from:

Biomass
Type      Lower  Center    Upper     +---------+---------+---------+------
UU       -3.178  -1.817  -0.4550     (--------*-------)
                                     +---------+---------+---------+------
                                  -3.2      -1.6       0.0       1.6


Tukey Simultaneous Tests
Response Variable Oil Yield
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
PW           1.2833      0.5455   2.3525    0.0675
UU          -0.5333      0.5455  -0.9777    0.5977


Biomass Type = PW  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
UU           -1.817      0.5455   -3.330    0.0076


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Oil Yield
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

Temp     Lower  Center  Upper     +---------+---------+---------+------
450   -0.04823   1.689  3.426               (------*------)
```

```
475    1.41843   3.156  4.893                     (------*------)
500    0.55177   2.289  4.026                 (------*------)
                                    +---------+---------+---------+------
                                 -2.5       0.0       2.5       5.0
```

Temp = 450 subtracted from:

```
Temp   Lower  Center  Upper     +---------+---------+---------+------
475   -0.270  1.4667  3.204              (------*------)
500   -1.137  0.6000  2.337          (------*------)
                                +---------+---------+---------+------
                             -2.5       0.0       2.5       5.0
```

Temp = 475 subtracted from:

```
Temp   Lower   Center   Upper     +---------+---------+---------+------
500   -2.604  -0.8667  0.8705     (------*-----)
                                  +---------+---------+---------+------
                               -2.5       0.0       2.5       5.0
```

Tukey Simultaneous Tests
Response Variable Oil Yield
All Pairwise Comparisons among Levels of Temp
Temp = 425 subtracted from:

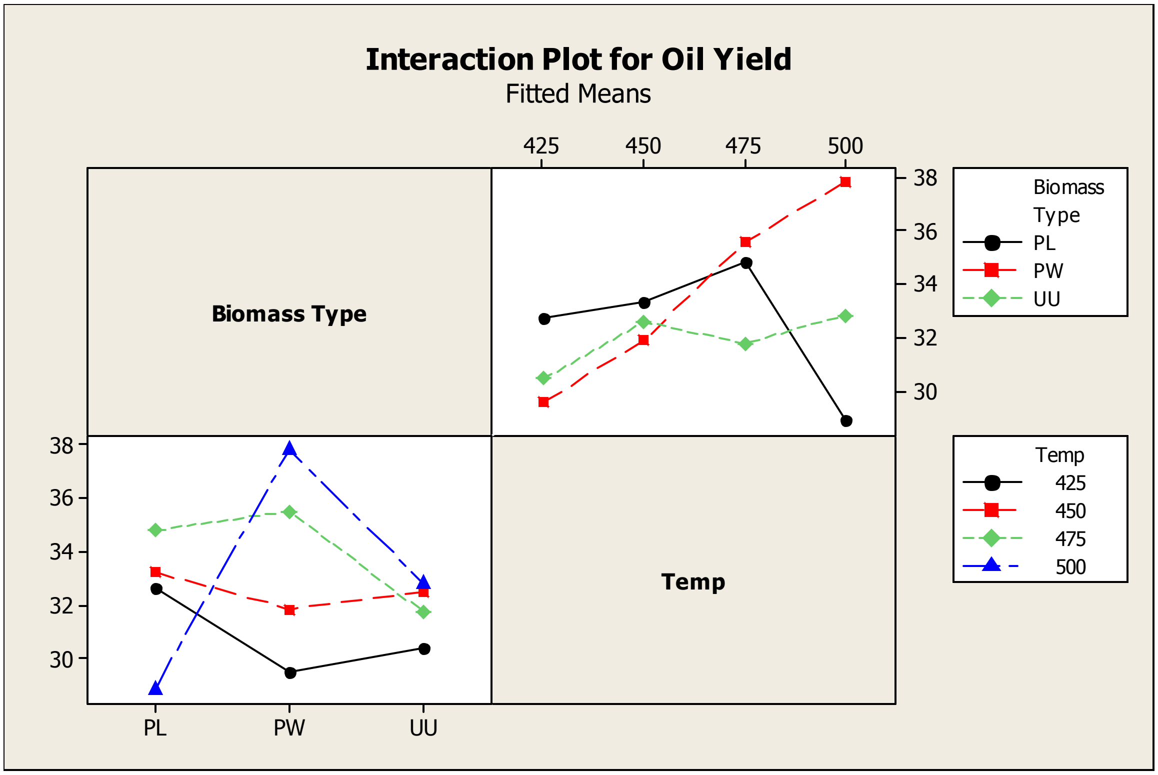
Temp	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
450	1.689	0.6299	2.681	0.0589
475	3.156	0.6299	5.010	0.0002
500	2.289	0.6299	3.634	0.0068

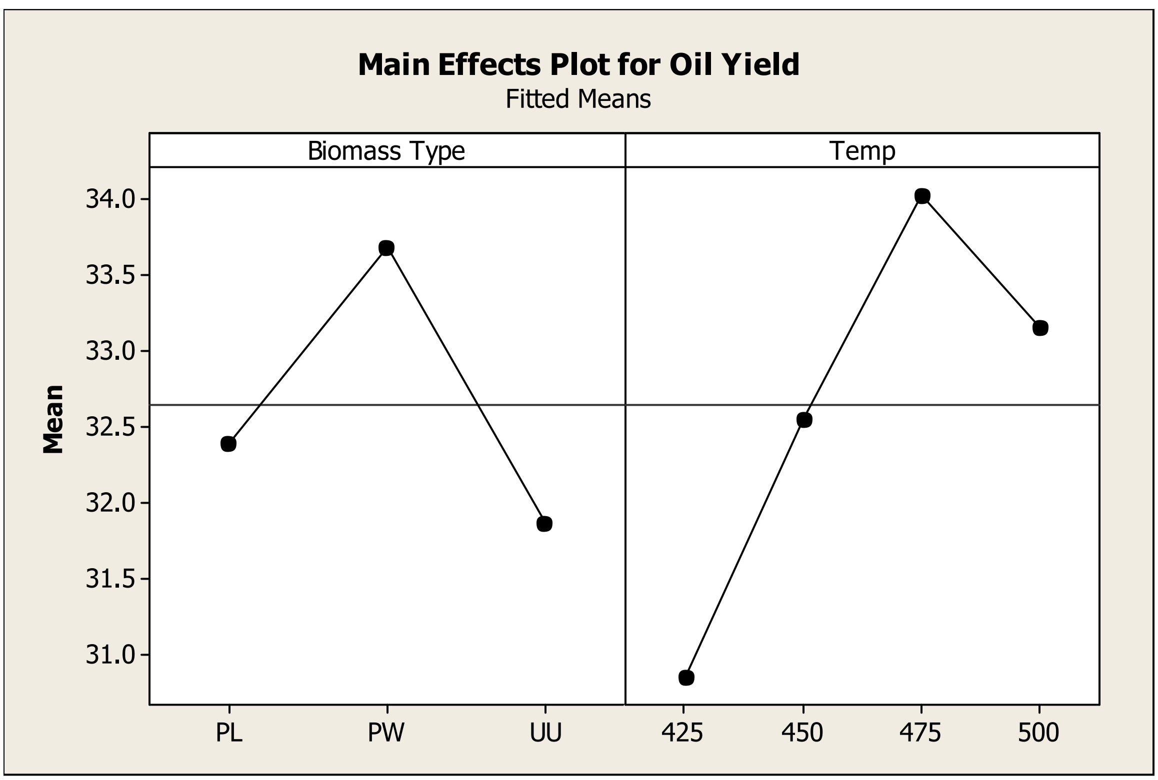
Temp = 450 subtracted from:

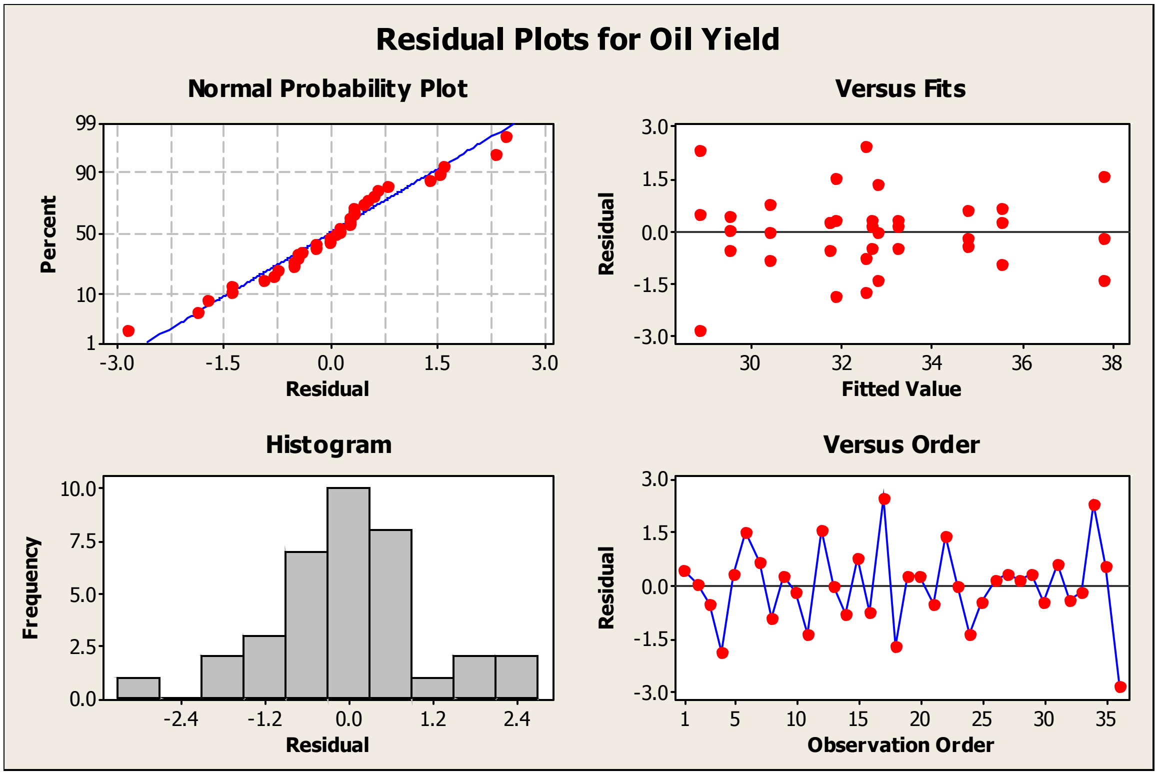
Temp	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
475	1.4667	0.6299	2.3284	0.1196
500	0.6000	0.6299	0.9525	0.7771

Temp = 475 subtracted from:

Temp	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
500	-0.8667	0.6299	-1.376	0.5259


Interaction Plot for Oil Yield
Fitted Means
425
450
475
500
38
36
34
32
30
Biomass Type
Biomass Type
PL
PW
UU
Temp
425
450
475
500
Temp
38
36
34
32
30
PL
PW
UU


Main Effects Plot for Oil Yield
Fitted Means
Biomass Type
Temp
Mean
34.0
33.5
33.0
32.5
32.0
31.5
31.0
PL
PW
UU
425
450
475
500



Minitab worksheet for biochar production:

Biomass Type	Temp	Char Yield
PW	425	48.8
PW	425	49.6
PW	425	50.4
PW	450	43
PW	450	37.8
PW	450	41.2
PW	475	32.2
PW	475	34.2
PW	475	32.8
PW	500	28.4
PW	500	23.6
PW	500	21
UU	425	38.6
UU	425	48
UU	425	39.6
UU	450	40.8
UU	450	36.4
UU	450	40.4

Biomass Type	Temp	Char Yield
UU	475	39
UU	475	40.4
UU	475	34.4
UU	500	31
UU	500	30.2
UU	500	24
PL	425	49.4
PL	425	48.4
PL	425	47.2
PL	450	43
PL	450	42.6
PL	450	45.6
PL	475	39.6
PL	475	40.8
PL	475	40.8
PL	500	36
PL	500	38.4
PL	500	39.2

Minitab result for biochar production:

Two-way ANOVA: Char versus Biomass Type, Temp

```
Source        DF       SS       MS      F      P
Biomass Type   2   257.65  128.823  17.77  0.000
Temp           3  1299.44  433.147  59.75  0.000
Interaction    6   244.94   40.823   5.63  0.001
Error         24   173.97    7.249
Total         35  1976.00

S = 2.692   R-Sq = 91.20%   R-Sq(adj) = 87.16%


                  Individual 95% CIs For Mean Based on
Biomass           Pooled StDev
Type        Mean  ---------+---------+---------+---------+
PL       42.5833                       (-----*------)
PW       36.9167  (------*-----)
UU       36.9000  (------*-----)
                  ---------+---------+---------+---------+
                        37.5      40.0      42.5      45.0


               Individual 95% CIs For Mean Based on
               Pooled StDev
Temp     Mean  ---+---------+---------+---------+------
425   46.6667                             (--*--)
450   41.2000                    (--*--)
475   37.1333             (--*--)
```

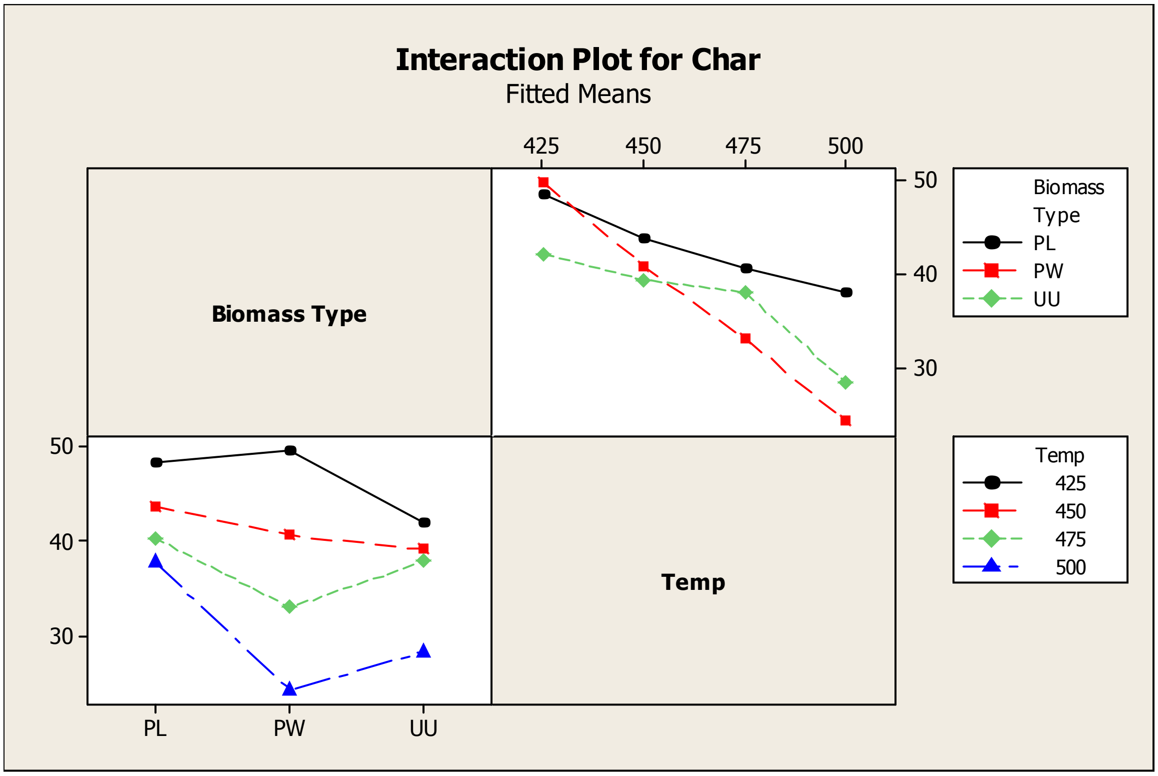
```
500   30.2000  (--*--)
               ---+---------+---------+---------+------
               30.0      36.0      42.0      48.0
```

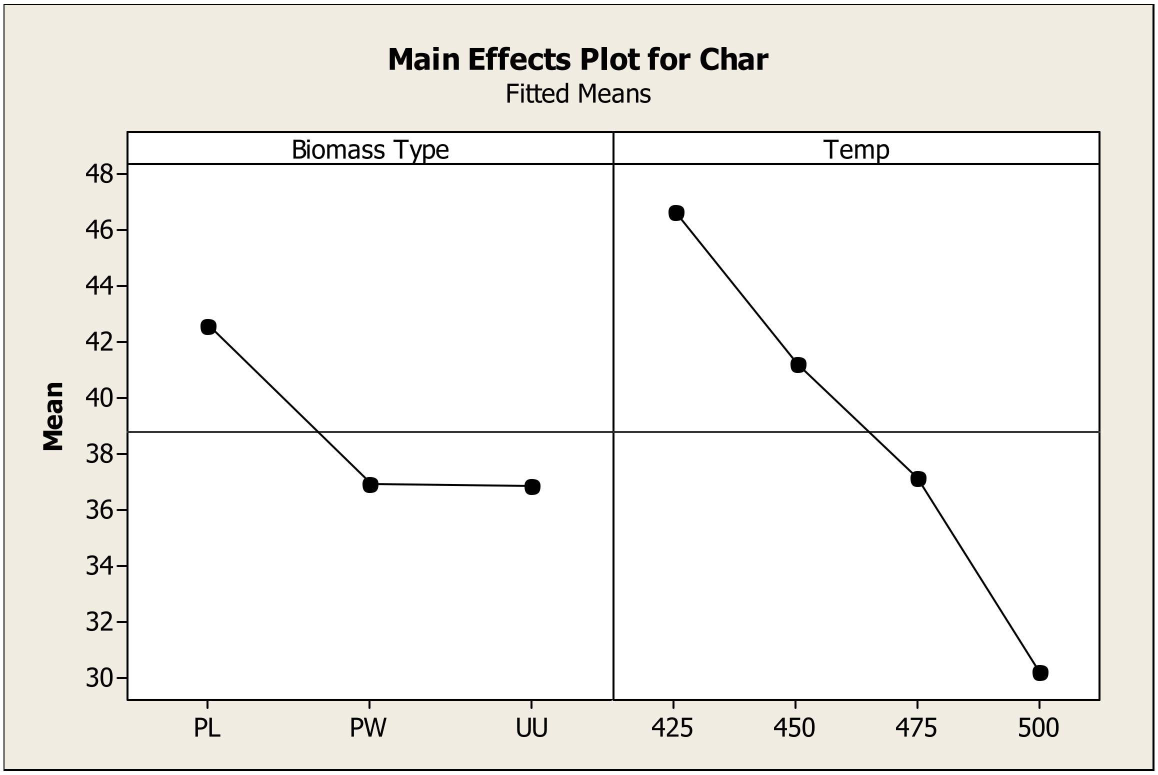
General Linear Model: Char versus Biomass Type, Temp

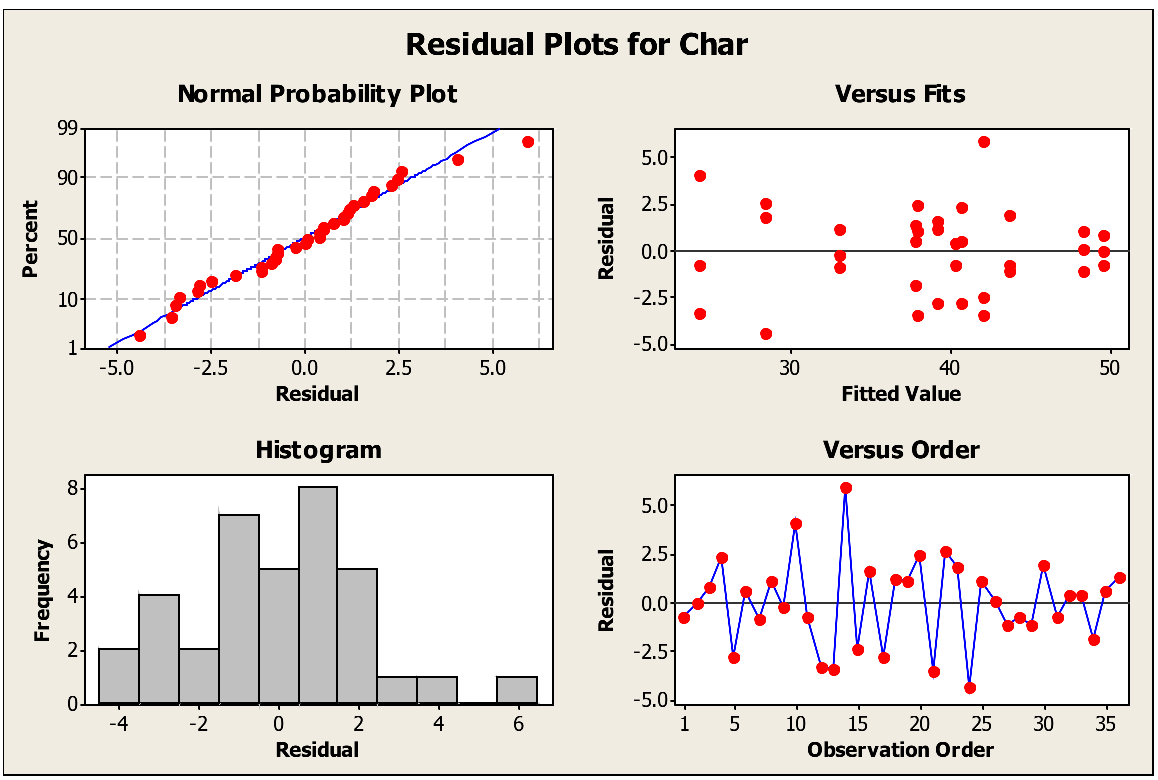
```
Factor        Type   Levels  Values
Biomass Type  fixed       3  PL, PW, UU
Temp          fixed       4  425, 450, 475, 500


Analysis of Variance for Char, using Adjusted SS for Tests

Source             DF   Seq SS   Adj SS  Adj MS      F      P
Biomass Type        2   257.65   257.65  128.82  17.77  0.000
Temp                3  1299.44  1299.44  433.15  59.75  0.000
Biomass Type*Temp   6   244.94   244.94   40.82   5.63  0.001
Error              24   173.97   173.97    7.25
Total              35  1976.00


S = 2.69238   R-Sq = 91.20%   R-Sq(adj) = 87.16%


Unusual Observations for Char

Obs     Char      Fit  SE Fit  Residual  St Resid
 14  48.0000  42.0667  1.5544    5.9333      2.70 R
 24  24.0000  28.4000  1.5544   -4.4000     -2.00 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Char
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass
Type      Lower  Center   Upper  ----+---------+---------+---------+--
PW       -8.410  -5.667  -2.923  (-------*-------)
UU       -8.427  -5.683  -2.940  (-------*-------)
                                 ----+---------+---------+---------+--
                                  -7.0      -3.5       0.0       3.5


Biomass Type = PW  subtracted from:

Biomass
Type      Lower    Center  Upper  ----+---------+---------+---------+--
UU       -2.760  -0.01667  2.727                 (-------*-------)
                                  ----+---------+---------+---------+--
                                   -7.0      -3.5       0.0       3.5


Tukey Simultaneous Tests
Response Variable Char
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass  Difference       SE of           Adjusted
```

```
Type       of Means  Difference  T-Value   P-Value
PW           -5.667       1.099   -5.155    0.0001
UU           -5.683       1.099   -5.171    0.0001


Biomass Type = PW  subtracted from:

Biomass  Difference       SE of            Adjusted
Type       of Means  Difference   T-Value   P-Value
UU         -0.01667       1.099  -0.01516    0.9999


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Char
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

Temp   Lower  Center   Upper   ---+---------+---------+---------+---
450    -8.97   -5.47   -1.97                     (-----*-----)
475   -13.03   -9.53   -6.03              (-----*-----)
500   -19.97  -16.47  -12.97   (-----*----)
                               ---+---------+---------+---------+---
                              -18.0     -12.0      -6.0       0.0


Temp = 450  subtracted from:

Temp   Lower  Center   Upper   ---+---------+---------+---------+---
475    -7.57   -4.07  -0.567                       (-----*-----)
500   -14.50  -11.00  -7.500            (-----*-----)
                               ---+---------+---------+---------+---
                              -18.0     -12.0      -6.0       0.0


Temp = 475  subtracted from:

Temp   Lower  Center   Upper   ---+---------+---------+---------+---
500   -10.43  -6.933  -3.433                    (----*-----)
                               ---+---------+---------+---------+---
                              -18.0     -12.0      -6.0       0.0


Tukey Simultaneous Tests
Response Variable Char
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
450        -5.47       1.269    -4.31    0.0013
475        -9.53       1.269    -7.51    0.0000
500       -16.47       1.269   -12.97    0.0000


Temp = 450  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
475        -4.07       1.269   -3.204    0.0186
500       -11.00       1.269   -8.667    0.0000


Temp = 475  subtracted from:
```

```
        Difference        SE of            Adjusted
Temp      of Means  Difference  T-Value     P-Value
500         -6.933       1.269   -5.463      0.0001
```




Main Effects Plot for Char
Fitted Means
Biomass Type
Temp
Mean
48
46
44
42
40
38
36
34
32
30
PL
PW
UU
425
450
475
500


Residual Plots for Char
Normal Probability Plot
Percent
99
90
50
10
1
-5.0
-2.5
0.0
2.5
5.0
Residual
Versus Fits
Residual
5.0
2.5
0.0
-2.5
-5.0
30
40
50
Fitted Value
Histogram
Frequency
8
6
4
2
0
-4
-2
0
2
4
6
Residual
Versus Order
Residual
5.0
2.5
0.0
-2.5
-5.0
1
5
10
15
20
25
30
35
Observation Order

Minitab worksheet for gas production:

Biomass Type	Temp	Gas Yield
PW	425	21.2
PW	425	20.8
PW	425	20.6
PW	450	27
PW	450	30
PW	450	25.4
PW	475	31.6
PW	475	31.2
PW	475	31.4
PW	500	34
PW	500	40
PW	500	39.6
UU	425	31
UU	425	22.4
UU	425	29.2
UU	450	27.4
UU	450	28.6
UU	450	28.8
UU	475	29
UU	475	27.6
UU	475	34.4
UU	500	34.8
UU	500	37
UU	500	44.6
PL	425	18.4
PL	425	18.8
PL	425	19.8
PL	450	23.6
PL	450	23.8
PL	450	21.6
PL	475	25
PL	475	24.8
PL	475	24.6
PL	500	32.8
PL	500	32.2
PL	500	34.8

Minitab result for gas production:

Two-way ANOVA: Gas Yield versus Biomass Type, Temp

Source	DF	SS	MS	F	P
Biomass Type	2	244.89	122.443	18.09	0.000
Temp	3	971.36	323.788	47.84	0.000
Interaction	6	52.15	8.692	1.28	0.302
Error	24	162.43	6.768		
Total	35	1430.83			

S = 2.601   R-Sq = 88.65%   R-Sq(adj) = 83.45%

```
                  Individual 95% CIs For Mean Based on
Biomass           Pooled StDev
Type        Mean  ------+---------+---------+---------+---
PL       25.0167  (-----*-----)
PW       29.4000                   (------*-----)
UU       31.2333                           (-----*-----)
                  ------+---------+---------+---------+---
                     25.0      27.5      30.0      32.5


               Individual 95% CIs For Mean Based on
               Pooled StDev
Temp     Mean  ---------+---------+---------+---------+
425   22.4667  (---*---)
450   26.2444          (--*---)
475   28.8444               (---*--)
500   36.6444                              (--*---)
               ---------+---------+---------+---------+
                     25.0      30.0      35.0      40.0
```

General Linear Model: Gas Yield versus Biomass Type, Temp

Factor	Type	Levels	Values
Biomass Type	fixed	3	PL, PW, UU
Temp	fixed	4	425, 450, 475, 500

Analysis of Variance for Gas Yield, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Biomass Type	2	244.89	244.89	122.44	18.09	0.000
Temp	3	971.36	971.36	323.79	47.84	0.000
Biomass Type*Temp	6	52.15	52.15	8.69	1.28	0.302
Error	24	162.43	162.43	6.77		
Total	35	1430.83				

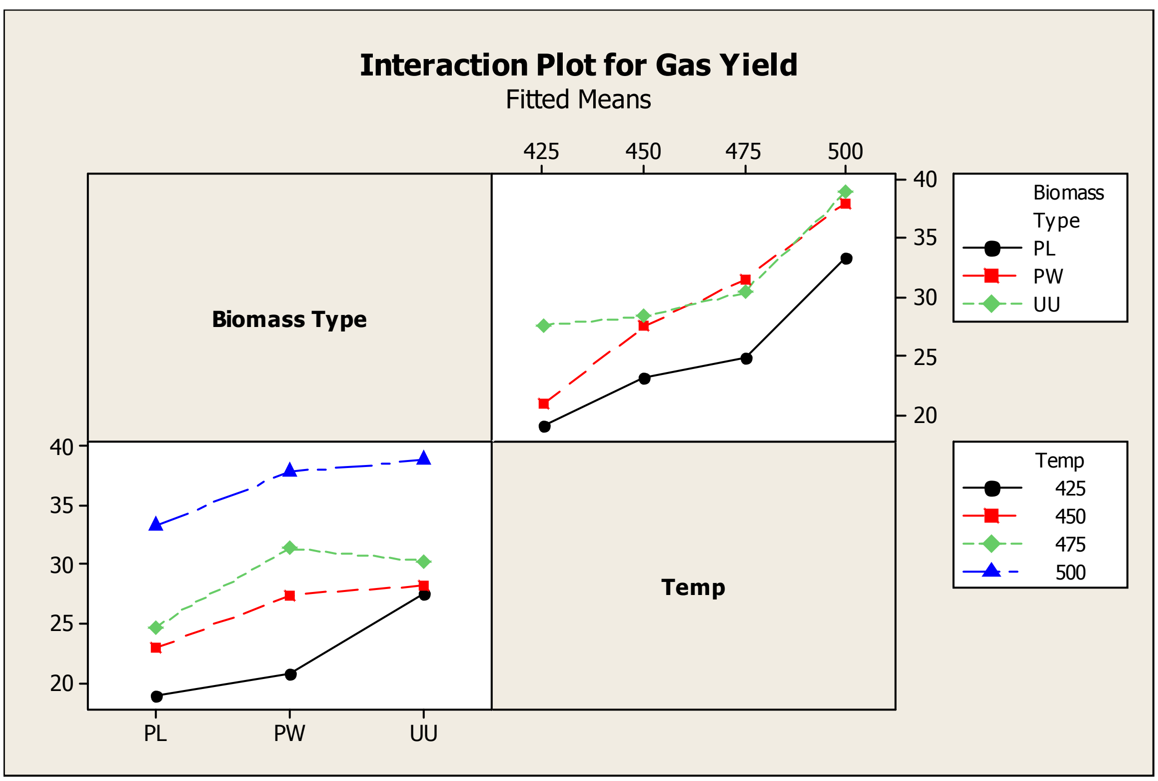
S = 2.60150   R-Sq = 88.65%   R-Sq(adj) = 83.45%

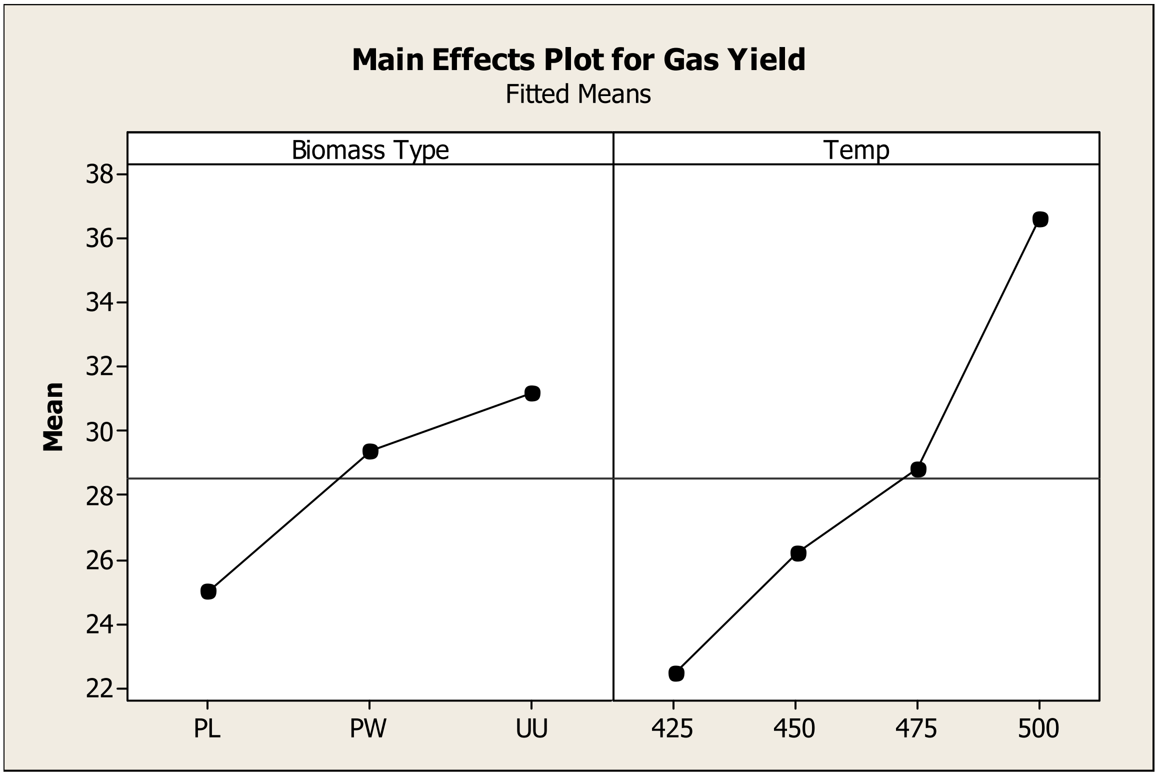
Unusual Observations for Gas Yield

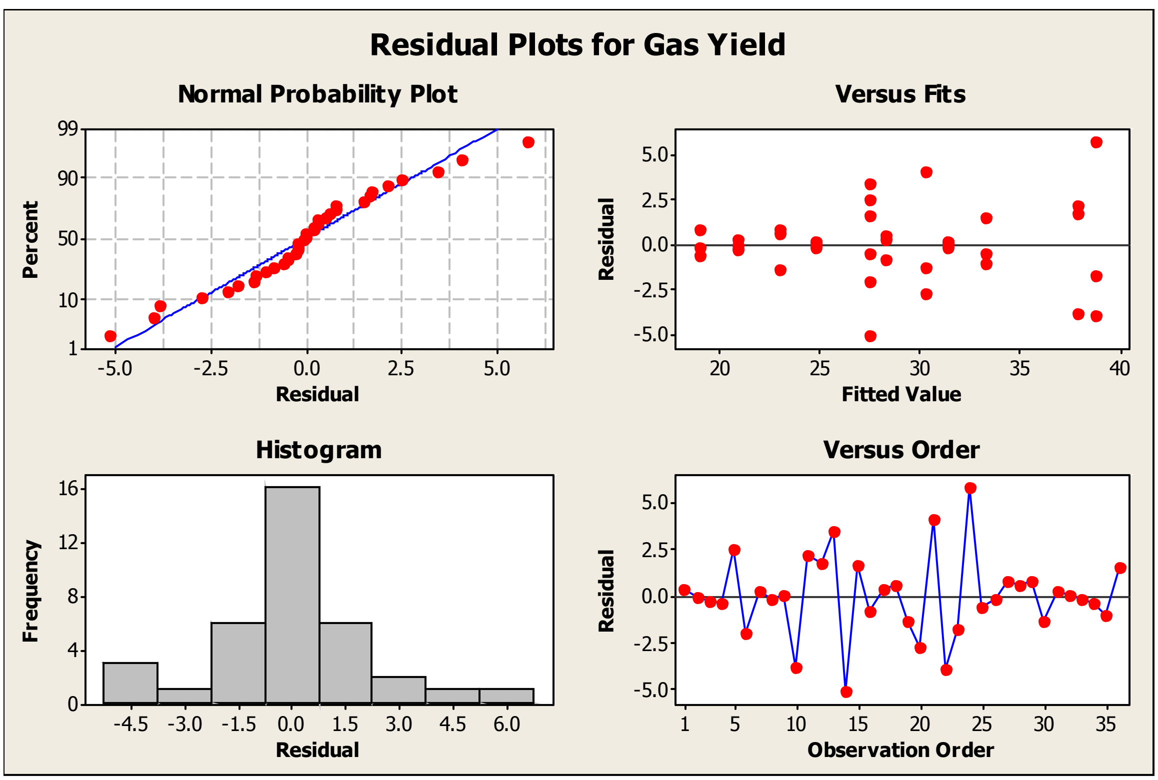
Obs	Gas Yield	Fit	SE Fit	Residual	St Resid	
14	22.4000	27.5333	1.5020	-5.1333	-2.42	R
24	44.6000	38.8000	1.5020	5.8000	2.73	R

```
R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Gas Yield
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass
Type     Lower  Center  Upper  ---+---------+---------+---------+---
PW       1.732   4.383  7.034          (--------*-------)
UU       3.566   6.217  8.868                (--------*--------)
                               ---+---------+---------+---------+---
                                 0.0       3.0       6.0       9.0


Biomass Type = PW  subtracted from:

Biomass
Type       Lower  Center  Upper  ---+---------+---------+---------+---
UU       -0.8177   1.833  4.484  (--------*--------)
                                 ---+---------+---------+---------+---
                                   0.0       3.0       6.0       9.0


Tukey Simultaneous Tests
Response Variable Gas Yield
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
PW            4.383       1.062    4.127    0.0011
UU            6.217       1.062    5.853    0.0000


Biomass Type = PW  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
UU            1.833       1.062    1.726    0.2162


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Gas Yield
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

Temp    Lower  Center   Upper  --+---------+---------+---------+----
450    0.3958   3.778   7.160     (------*-----)
475    2.9958   6.378   9.760          (------*------)
500   10.7958  14.178  17.560                         (-----*------)
                               --+---------+---------+---------+----
                               0.0       5.0      10.0      15.0


Temp = 450  subtracted from:

Temp    Lower  Center   Upper  --+---------+---------+---------+----
475   -0.7819   2.600   5.982  (------*------)
500    7.0181  10.400  13.782                 (------*------)
                               --+---------+---------+---------+----
```

```
                                        0.0       5.0      10.0      15.0
Temp = 475  subtracted from:

Temp  Lower  Center  Upper  --+---------+---------+---------+----
500   4.418   7.800  11.18             (------*-----)
                            --+---------+---------+---------+----
                            0.0       5.0      10.0      15.0


Tukey Simultaneous Tests
Response Variable Gas Yield
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
450        3.778       1.226    3.080     0.0246
475        6.378       1.226    5.201     0.0001
500       14.178       1.226   11.561     0.0000


Temp = 450  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
475        2.600       1.226    2.120     0.1754
500       10.400       1.226    8.480     0.0000


Temp = 475  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
500        7.800       1.226    6.360     0.0000
```




Main Effects Plot for Gas Yield
Fitted Means
Biomass Type
Temp
Mean
38
36
34
32
30
28
26
24
22
PL
PW
UU
425
450
475
500


Residual Plots for Gas Yield
Normal Probability Plot
Percent
99
90
50
10
1
-5.0
-2.5
0.0
2.5
5.0
Residual
Versus Fits
Residual
5.0
2.5
0.0
-2.5
-5.0
20
25
30
35
40
Fitted Value
Histogram
Frequency
16
12
8
4
0
-4.5
-3.0
-1.5
0.0
1.5
3.0
4.5
6.0
Residual
Versus Order
Residual
5.0
2.5
0.0
-2.5
-5.0
1
5
10
15
20
25
30
35
Observation Order

Minitab worksheet for density of bio-oil:

Biomass Type	Temp	Density	Biomass Type	Temp	Density	Biomass Type	Temp	Density
PW	425	1156.65	UU	425	1212.05	PL	425	1054.7
PW	425	1154.8	UU	425	1181.1	PL	425	1057.95
PW	425	1144.65	UU	425	1177.85	PL	425	1137.5
PW	450	1135.35	UU	450	1207.15	PL	450	1058.3
PW	450	1161.7	UU	450	1174.85	PL	450	1054.4
PW	450	1145.05	UU	450	1189.75	PL	450	1087.75
PW	475	1116.8	UU	475	1177.5	PL	475	1059
PW	475	1147.2	UU	475	1195.85	PL	475	1077.15
PW	475	1130.4	UU	475	1174.85	PL	475	1067.6
PW	500	1120.8	UU	500	1178.3	PL	500	1062.1
PW	500	1167.8	UU	500	1180.65	PL	500	1064.05
PW	500	1126.3	UU	500	1169.4	PL	500	1062.05
PW	425	1154.8	UU	425	1211.65	PL	425	1054.15
PW	425	1152.25	UU	425	1177.1	PL	425	1050.9
PW	425	1140.8	UU	425	1172.8	PL	425	1134.05
PW	450	1147.5	UU	450	1184.2	PL	450	1051.7
PW	450	1169.65	UU	450	1182	PL	450	1055.95
PW	450	1142.2	UU	450	1174	PL	450	1081.1
PW	475	1101.9	UU	475	1180.55	PL	475	1049.2
PW	475	1146.45	UU	475	1184.9	PL	475	1079.3
PW	475	1180.3	UU	475	1179.75	PL	475	1045.3
PW	500	1096.2	UU	500	1172.5	PL	500	1060.05
PW	500	1152.65	UU	500	1179.9	PL	500	1061.45
PW	500	1126.85	UU	500	1154.65	PL	500	1064.25
PW	425	1157.85	UU	425	1208.15	PL	425	1054.4
PW	425	1168.25	UU	425	1184.15	PL	425	1054.85
PW	425	1144.2	UU	425	1173.6	PL	425	1135.75
PW	450	1136.25	UU	450	1189.1	PL	450	1056.9
PW	450	1169.75	UU	450	1186.95	PL	450	1052.45
PW	450	1142.5	UU	450	1181.5	PL	450	1084.95
PW	475	1135.45	UU	475	1178.85	PL	475	1062.65
PW	475	1125.1	UU	475	1199.45	PL	475	1069.55
PW	475	1125.45	UU	475	1161.3	PL	475	1059.5
PW	500	1130.45	UU	500	1161.9	PL	500	1065.6
PW	500	1148.65	UU	500	1182.4	PL	500	1056.4
PW	500	1117.2	UU	500	1159.05	PL	500	1065.45

Minitab result for density of bio-oil:

Two-way ANOVA: Density versus Biomass type, Temp

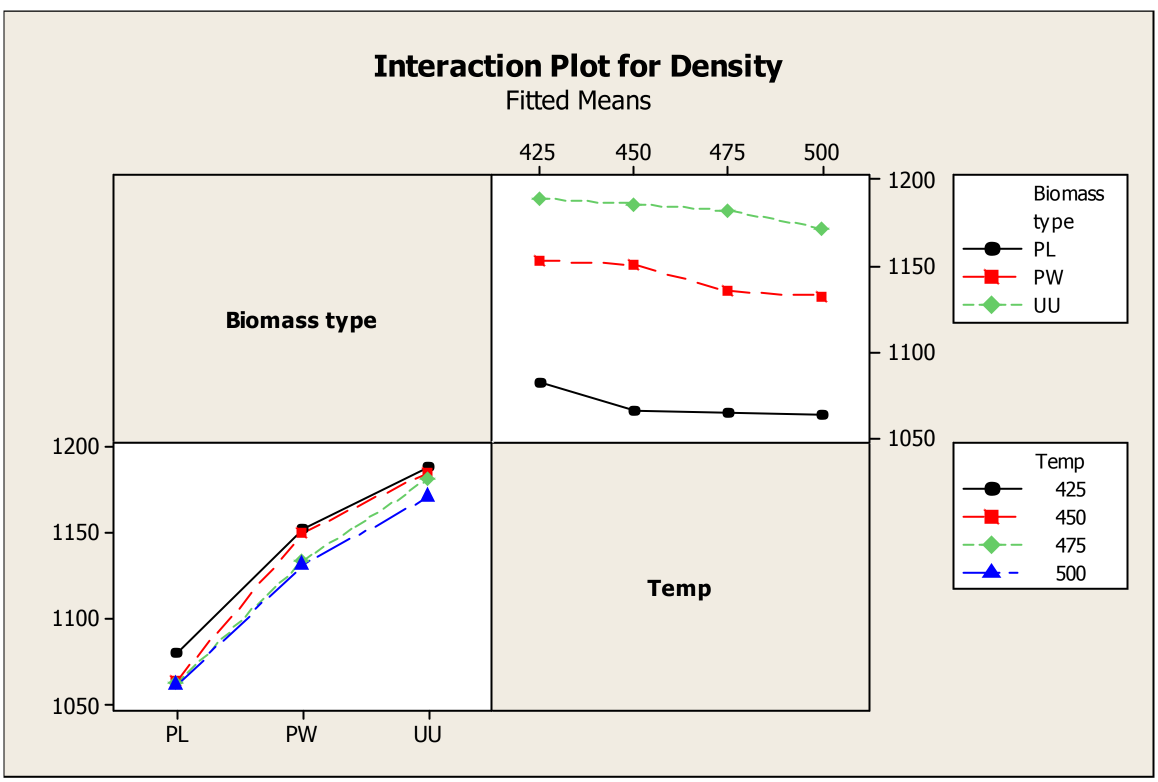
```
Source         DF      SS      MS       F      P
Biomass type    2  239742  119871  373.97  0.000
Temp            3    5745    1915    5.97  0.001
Interaction     6    1156     193    0.60  0.729
Error          96   30772     321
Total         107  277414

S = 17.90   R-Sq = 88.91%   R-Sq(adj) = 87.64%


                  Individual 95% CIs For Mean Based on
Biomass           Pooled StDev
type        Mean  -------+---------+---------+---------+--
PL       1068.01  (-*-)
PW       1142.23                        (*-)
UU       1181.66                                   (-*)
                  -------+---------+---------+---------+--
                      1085      1120      1155      1190


               Individual 95% CIs For Mean Based on
               Pooled StDev
Temp     Mean  -----+---------+---------+---------+----
425   1141.00                    (------*------)
450   1133.44             (-----*------)
475   1126.34      (-----*------)
500   1121.74  (------*------)
               -----+---------+---------+---------+----
                 1120      1130      1140      1150
```

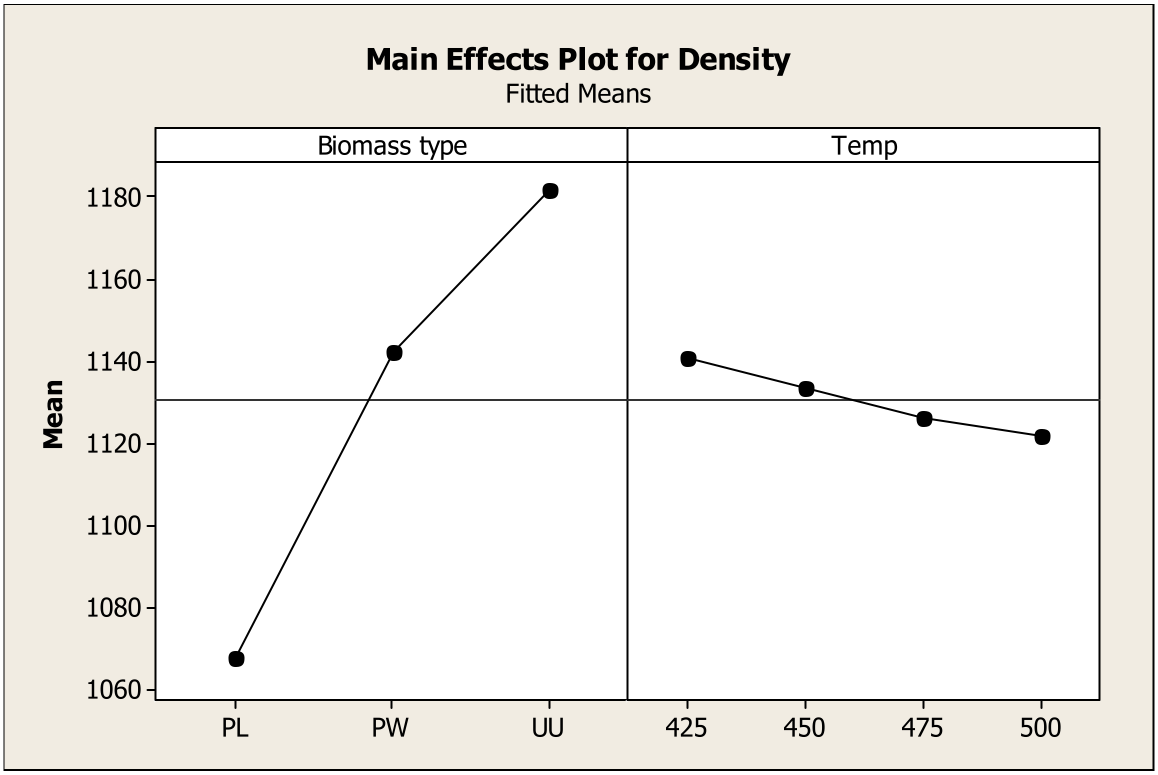
General Linear Model: Density versus Biomass type, Temp

```
Factor        Type   Levels  Values
Biomass type  fixed       3  PL, PW, UU
Temp          fixed       4  425, 450, 475, 500


Analysis of Variance for Density, using Adjusted SS for Tests

Source              DF  Seq SS  Adj SS  Adj MS       F      P
Biomass type         2  239742  239742  119871  373.97  0.000
Temp                 3    5745    5745    1915    5.97  0.001
Biomass type*Temp    6    1156    1156     193    0.60  0.729
Error               96   30772   30772     321
Total              107  277414


S = 17.9036   R-Sq = 88.91%   R-Sq(adj) = 87.64%


Unusual Observations for Density

Obs  Density      Fit  SE Fit  Residual  St Resid
 11  1167.80  1131.88    5.97     35.92      2.13 R
 21  1180.30  1134.34    5.97     45.96      2.72 R
 22  1096.20  1131.88    5.97    -35.68     -2.11 R
```

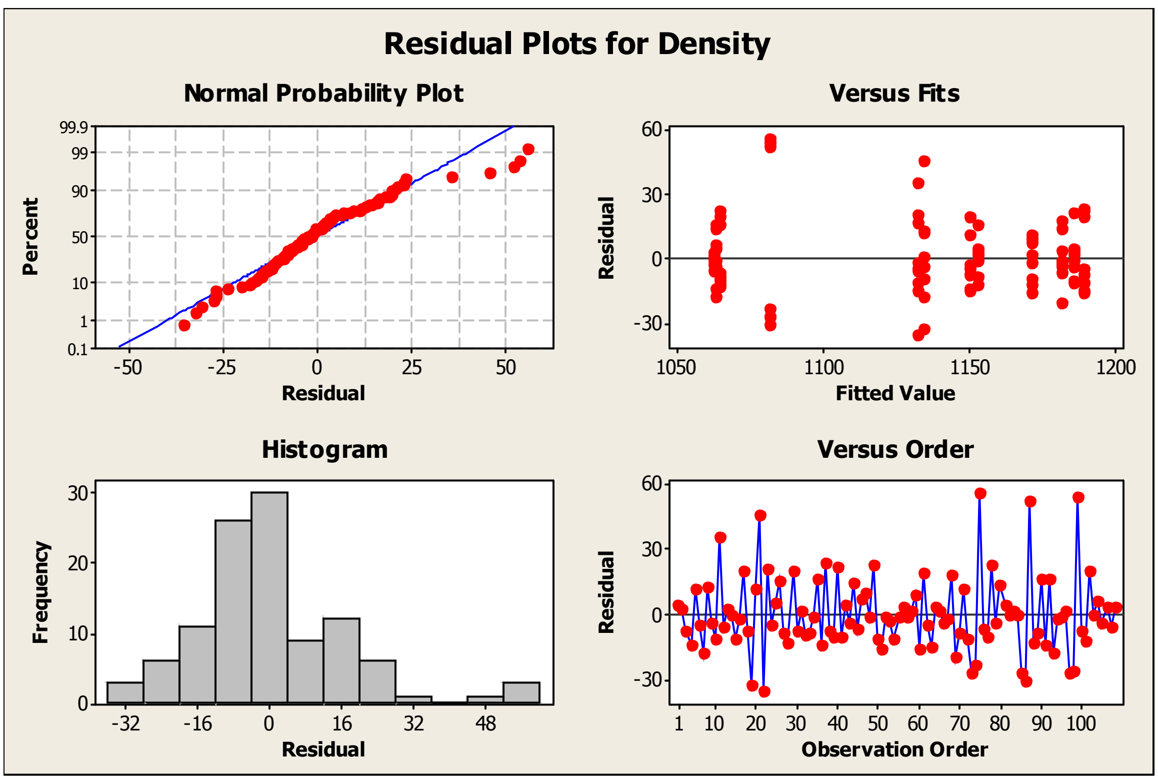
```
 75  1137.50  1081.58    5.97     55.92      3.31 R
 87  1134.05  1081.58    5.97     52.47      3.11 R
 99  1135.75  1081.58    5.97     54.17      3.21 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Density
All Pairwise Comparisons among Levels of Biomass type
Biomass type = PL  subtracted from:

Biomass
type      Lower  Center   Upper   +---------+---------+---------+------
PW        64.16   74.22   84.27             (---*--)
UU       103.59  113.65  123.70                            (--*--)
                                  +---------+---------+---------+------
                                 30        60        90       120


Biomass type = PW  subtracted from:

Biomass
type     Lower  Center  Upper   +---------+---------+---------+------
UU       29.38   39.43  49.49   (--*--)
                                +---------+---------+---------+------
                               30        60        90       120
Tukey Simultaneous Tests
Response Variable Density
All Pairwise Comparisons among Levels of Biomass type
Biomass type = PL  subtracted from:

Biomass  Difference       SE of           Adjusted
type       of Means  Difference  T-Value   P-Value
PW            74.22       4.220    17.59    0.0000
UU           113.65       4.220    26.93    0.0000


Biomass type = PW  subtracted from:

Biomass  Difference       SE of           Adjusted
type       of Means  Difference  T-Value   P-Value
UU            39.43       4.220    9.344    0.0000

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Density
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

Temp   Lower  Center   Upper  -------+---------+---------+---------
450   -20.30   -7.56   5.193           (----------*---------)
475   -27.40  -14.65  -1.905      (----------*---------)
500   -32.00  -19.26  -6.507  (----------*----------)
                              -------+---------+---------+---------
                                   -24       -12         0
Temp = 450  subtracted from:

Temp   Lower  Center  Upper  -------+---------+---------+---------
475   -19.85   -7.10  5.650           (----------*----------)
500   -24.45  -11.70  1.049        (---------*----------)
                             -------+---------+---------+---------
                                  -24       -12         0
```

```
Temp = 475  subtracted from:

Temp   Lower  Center  Upper  -------+---------+---------+---------
500   -17.35  -4.602  8.147              (---------*----------)
                             -------+---------+---------+---------
                                  -24       -12         0

Tukey Simultaneous Tests
Response Variable Density
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
450        -7.56       4.873   -1.551     0.4118
475       -14.65       4.873   -3.007     0.0174
500       -19.26       4.873   -3.952     0.0009


Temp = 450  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
475        -7.10       4.873   -1.457     0.4676
500       -11.70       4.873   -2.401     0.0837

Temp = 475  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
500       -4.602       4.873  -0.9444     0.7810
```





Main Effects Plot for Density
Fitted Means
Biomass type
Temp
Mean
1060
1080
1100
1120
1140
1160
1180
PL
PW
UU
425
450
475
500



Residual Plots for Density
Normal Probability Plot
Percent
Residual
Versus Fits
Fitted Value
Histogram
Frequency
Versus Order
Observation Order

Minitab worksheet for pH value of bio-oil:

Biomass Type	Temp	pH	Biomass Type	Temp	pH	Biomass Type	Temp	pH
PW	425	3.31	UU	425	3.01	PL	425	9.23
PW	425	3.33	UU	425	2.90	PL	425	9.28
PW	425	3.36	UU	425	2.91	PL	425	9.24
PW	450	3.39	UU	450	3.08	PL	450	9.31
PW	450	3.43	UU	450	2.94	PL	450	9.32
PW	450	3.47	UU	450	2.92	PL	450	9.28
PW	475	3.63	UU	475	3.00	PL	475	9.31
PW	475	3.69	UU	475	3.06	PL	475	9.35
PW	475	3.69	UU	475	3.08	PL	475	9.33
PW	500	3.68	UU	500	3.06	PL	500	9.36
PW	500	3.74	UU	500	3.05	PL	500	9.44
PW	500	3.76	UU	500	3.19	PL	500	9.48
PW	425	3.31	UU	425	3.01	PL	425	9.23
PW	425	3.34	UU	425	2.89	PL	425	9.28
PW	425	3.36	UU	425	2.90	PL	425	9.23
PW	450	3.40	UU	450	3.07	PL	450	9.31
PW	450	3.43	UU	450	2.93	PL	450	9.31
PW	450	3.48	UU	450	2.92	PL	450	9.29
PW	475	3.63	UU	475	3.00	PL	475	9.31
PW	475	3.68	UU	475	3.06	PL	475	9.35
PW	475	3.69	UU	475	3.08	PL	475	9.34
PW	500	3.69	UU	500	3.06	PL	500	9.36
PW	500	3.73	UU	500	3.04	PL	500	9.44
PW	500	3.76	UU	500	3.19	PL	500	9.49
PW	425	3.31	UU	425	3.01	PL	425	9.25
PW	425	3.33	UU	425	2.88	PL	425	9.27
PW	425	3.35	UU	425	2.90	PL	425	9.23
PW	450	3.40	UU	450	3.07	PL	450	9.31
PW	450	3.43	UU	450	2.94	PL	450	9.32
PW	450	3.48	UU	450	2.91	PL	450	9.29
PW	475	3.64	UU	475	2.99	PL	475	9.31
PW	475	3.68	UU	475	3.06	PL	475	9.34
PW	475	3.69	UU	475	3.05	PL	475	9.34
PW	500	3.70	UU	500	3.06	PL	500	9.36
PW	500	3.73	UU	500	3.03	PL	500	9.44
PW	500	3.76	UU	500	3.18	PL	500	9.49

Minitab result for pH value of bio-oil:

Two-way ANOVA: pH versus Biomass Type, Temp

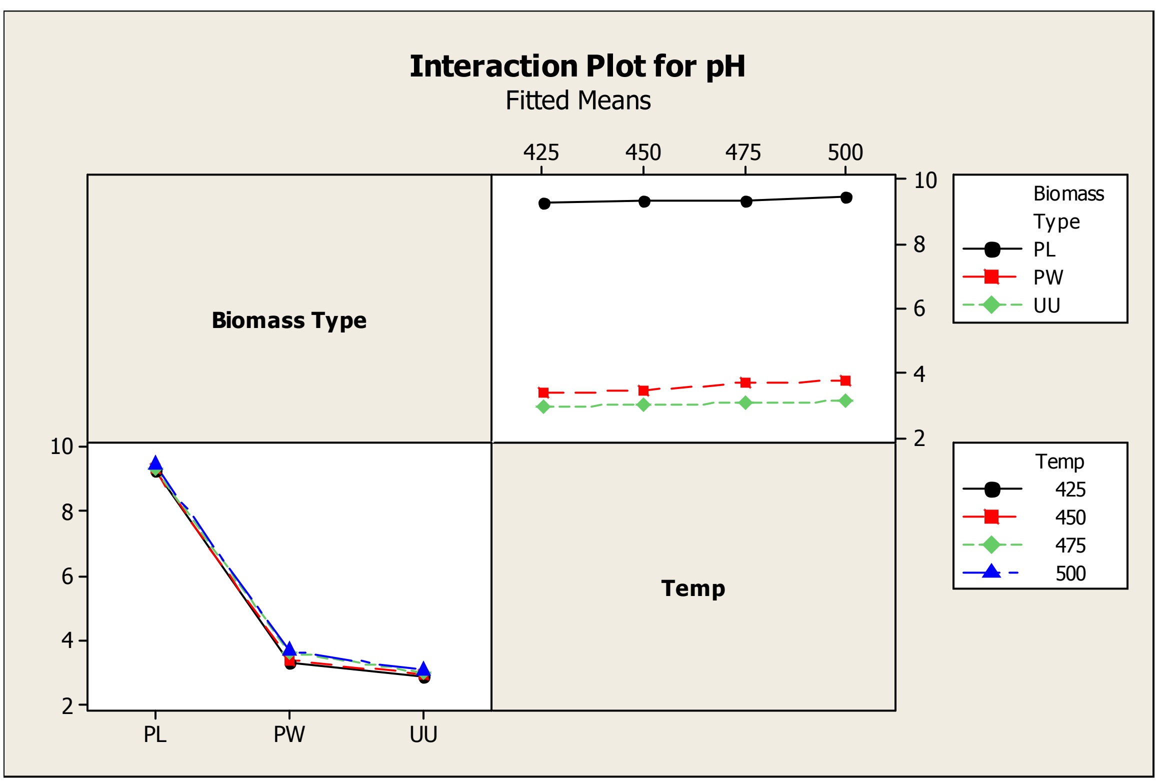
```
Source         DF       SS       MS          F      P
Biomass Type    2  884.025  442.012  238686.68  0.000
Temp            3    0.973    0.324     175.11  0.000
Interaction     6    0.269    0.045      24.19  0.000
Error          96    0.178    0.002
Total         107  885.444

S = 0.04303   R-Sq = 99.98%   R-Sq(adj) = 99.98%


                  Individual 95% CIs For Mean Based on
Biomass           Pooled StDev
Type        Mean   -+---------+---------+---------+--------
PL       9.32833                                          *
PW       3.54111      *
UU       3.01194   *
                   -+---------+---------+---------+--------
                  3.2       4.8       6.4       8.0


               Individual 95% CIs For Mean Based on
               Pooled StDev
Temp     Mean  ---+---------+---------+---------+------
425   5.17222  (-*-)
450   5.23815           (-*--)
475   5.34741                          (-*-)
500   5.41741                                    (-*-)
               ---+---------+---------+---------+------
                5.180     5.250     5.320     5.390
```

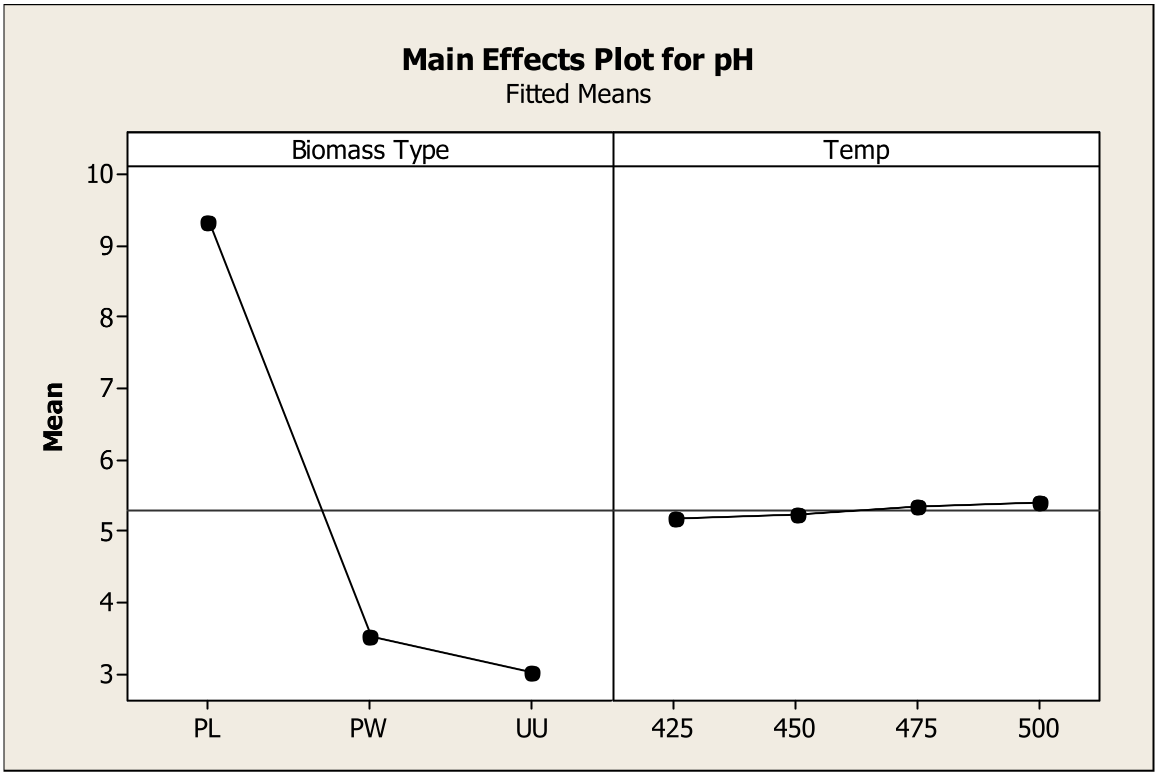
General Linear Model: pH versus Biomass Type, Temp

```
Factor        Type   Levels  Values
Biomass Type  fixed       3  PL, PW, UU
Temp          fixed       4  425, 450, 475, 500


Analysis of Variance for pH, using Adjusted SS for Tests

Source              DF   Seq SS   Adj SS   Adj MS          F      P
Biomass Type         2  884.025  884.025  442.012  238686.68  0.000
Temp                 3    0.973    0.973    0.324     175.11  0.000
Biomass Type*Temp    6    0.269    0.269    0.045      24.19  0.000
Error               96    0.178    0.178    0.002
Total              107  885.444


S = 0.0430331   R-Sq = 99.98%   R-Sq(adj) = 99.98%


Unusual Observations for pH

Obs       pH      Fit   SE Fit  Residual  St Resid
 40  3.08000  2.97556  0.01434   0.10444      2.57 R
 48  3.19000  3.09556  0.01434   0.09444      2.33 R
 52  3.07000  2.97556  0.01434   0.09444      2.33 R
```

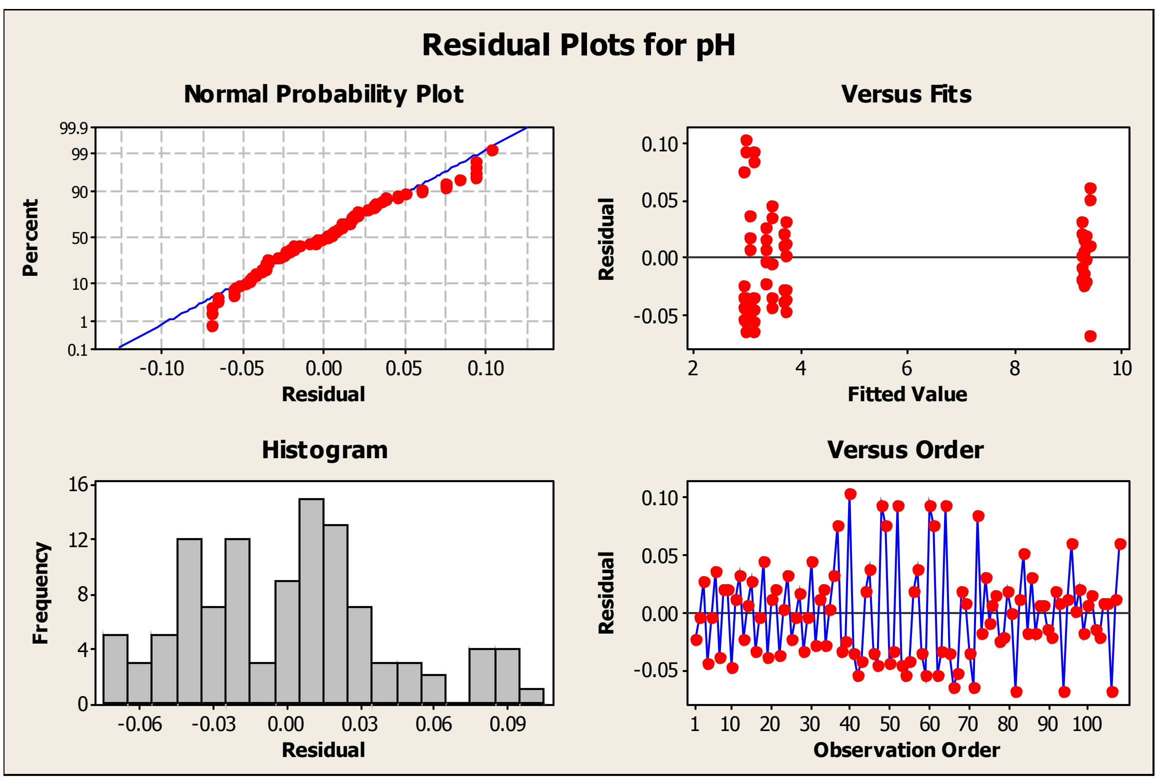
```
 60  3.19000  3.09556  0.01434   0.09444      2.33 R
 64  3.07000  2.97556  0.01434   0.09444      2.33 R
 72  3.18000  3.09556  0.01434   0.08444      2.08 R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable pH
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass
Type      Lower  Center   Upper   --+---------+---------+---------+----
PW       -5.811  -5.787  -5.763      *
UU       -6.341  -6.316  -6.292   *)
                                  --+---------+---------+---------+----
                                 -6.0      -4.0      -2.0       0.0
Biomass Type = PW  subtracted from:

Biomass
Type       Lower   Center    Upper   --+---------+---------+---------+----
UU       -0.5533  -0.5292  -0.5050                               *
                                     --+---------+---------+---------+----
                                    -6.0      -4.0      -2.0       0.0
Tukey Simultaneous Tests
Response Variable pH
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
PW           -5.787     0.01014   -570.6    0.0000
UU           -6.316     0.01014   -622.7    0.0000


Biomass Type = PW  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
UU          -0.5292     0.01014   -52.17    0.0000


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable pH
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

Temp    Lower   Center    Upper  -----+---------+---------+---------+-
450   0.03528  0.06593  0.09657  (---*----)
475   0.14454  0.17519  0.20583                 (---*---)
500   0.21454  0.24519  0.27583                           (---*---)
                                 -----+---------+---------+---------+-
                                    0.070     0.140     0.210     0.280


Temp = 450  subtracted from:

Temp    Lower  Center   Upper  -----+---------+---------+---------+-
475   0.07862  0.1093  0.1399       (----*---)
500   0.14862  0.1793  0.2099                 (----*---)
                               -----+---------+---------+---------+-
                                  0.070     0.140     0.210     0.280
```

```
Temp = 475  subtracted from:

Temp    Lower   Center   Upper  -----+---------+---------+---------+-
500   0.03936  0.07000  0.1006    (---*---)
                                -----+---------+---------+---------+-
                                   0.070     0.140     0.210     0.280


Tukey Simultaneous Tests
Response Variable pH
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
450      0.06593     0.01171    5.629     0.0000
475      0.17519     0.01171   14.958     0.0000
500      0.24519     0.01171   20.934     0.0000


Temp = 450  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
475       0.1093     0.01171    9.329     0.0000
500       0.1793     0.01171   15.305     0.0000

Temp = 475  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
500      0.07000     0.01171    5.977     0.0000
```





Main Effects Plot for pH
Fitted Means
Biomass Type
Temp
Mean
PL
PW
UU
425
450
475
500



Residual Plots for pH
Normal Probability Plot
Versus Fits
Percent
Residual
Histogram
Versus Order
Frequency
Fitted Value
Observation Order

Minitab worksheet for heating value of bio-oil:

Biomass Type	Temp	HHV	Biomass Type	Temp	HHV	Biomass Type	Temp	HHV
PW	425	19211	UU	425	17210	PL	425	10947
PW	425	19513	UU	425	19486	PL	425	11124
PW	425	20722	UU	425	20135	PL	425	11004
PW	450	20316	UU	450	19271	PL	450	11369
PW	450	20692	UU	450	20380	PL	450	12341
PW	450	21583	UU	450	21103	PL	450	13441
PW	475	20671	UU	475	20108	PL	475	14217
PW	475	21456	UU	475	19808	PL	475	14456
PW	475	21659	UU	475	19297	PL	475	14298
PW	500	21333	UU	500	18694	PL	500	14324
PW	500	22270	UU	500	18908	PL	500	13741
PW	500	22368	UU	500	19975	PL	500	13790
PW	425	19316	UU	425	19120	PL	425	10754
PW	425	19692	UU	425	20202	PL	425	10459
PW	425	20983	UU	425	20676	PL	425	11859
PW	450	20378	UU	450	20887	PL	450	12980
PW	450	20523	UU	450	20137	PL	450	12329
PW	450	21501	UU	450	20186	PL	450	12965
PW	475	20599	UU	475	21145	PL	475	13491
PW	475	21382	UU	475	19797	PL	475	14360
PW	475	21681	UU	475	20321	PL	475	14112
PW	500	21268	UU	500	19162	PL	500	14561
PW	500	22238	UU	500	18777	PL	500	13786
PW	500	22472	UU	500	21532	PL	500	14390
PW	425	19333	UU	425	18942	PL	425	10823
PW	425	19717	UU	425	20760	PL	425	11930
PW	425	21100	UU	425	19256	PL	425	11828
PW	450	20251	UU	450	20948	PL	450	12797
PW	450	20547	UU	450	20479	PL	450	11109
PW	450	21833	UU	450	21077	PL	450	12872
PW	475	20578	UU	475	21320	PL	475	13675
PW	475	21504	UU	475	21441	PL	475	14673
PW	475	21722	UU	475	20553	PL	475	14365
PW	500	21424	UU	500	19654	PL	500	13673
PW	500	22309	UU	500	18999	PL	500	13101
PW	500	22461	UU	500	21471	PL	500	13682

Minitab result for heating value of bio-oil:

Two-way ANOVA: HHV versus Biomass Type, Temp

Source	DF	SS	MS	F	P
Biomass Type	2	1400449083	700224542	1388.76	0.000
Temp	3	51168149	17056050	33.83	0.000
Interaction	6	26974632	4495772	8.92	0.000
Error	96	48404035	504209		
Total	107	1526995900			

S = 710.1   R-Sq = 96.83%   R-Sq(adj) = 96.47%

```
                  Individual 95% CIs For Mean Based on
Biomass           Pooled StDev
Type        Mean  ---------+---------+---------+---------+
PL       12934.1  (*)
PW       21016.8                                 (*)
UU       20033.8                             (*)
                  ---------+---------+---------+---------+
                       15000     17500     20000     22500
```

```
               Individual 95% CIs For Mean Based on
               Pooled StDev
Temp     Mean   ---+---------+---------+---------+------
425   16892.7   (----*---)
450   17936.9                  (----*---)
475   18618.1                              (---*----)
500   18532.0                            (----*---)
                ---+---------+---------+---------+------
               16800     17400     18000     18600
```

General Linear Model: HHV versus Biomass Type, Temp

Factor	Type	Levels	Values
Biomass Type	fixed	3	PL, PW, UU
Temp	fixed	4	425, 450, 475, 500

Analysis of Variance for HHV, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Biomass Type	2	1400449083	1400449083	700224542	1388.76	0.000
Temp	3	51168149	51168149	17056050	33.83	0.000
Biomass Type*Temp	6	26974632	26974632	4495772	8.92	0.000
Error	96	48404035	48404035	504209		
Total	107	1526995900				

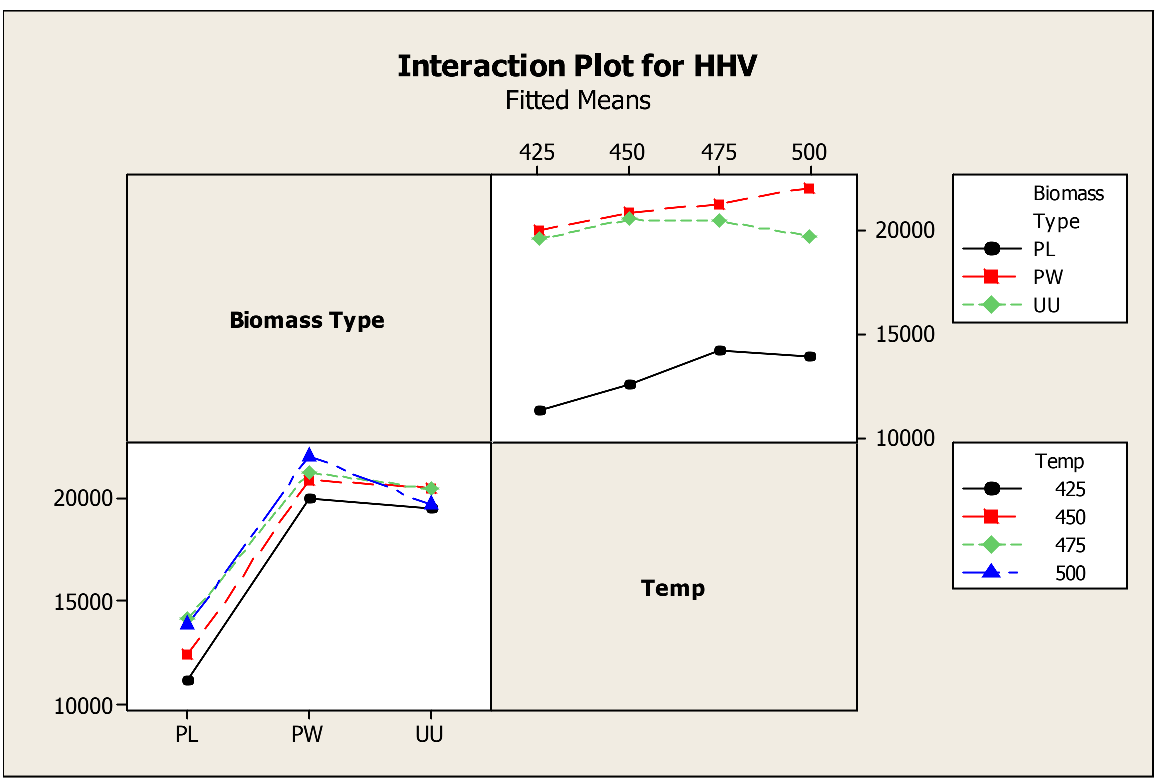
S = 710.077   R-Sq = 96.83%   R-Sq(adj) = 96.47%

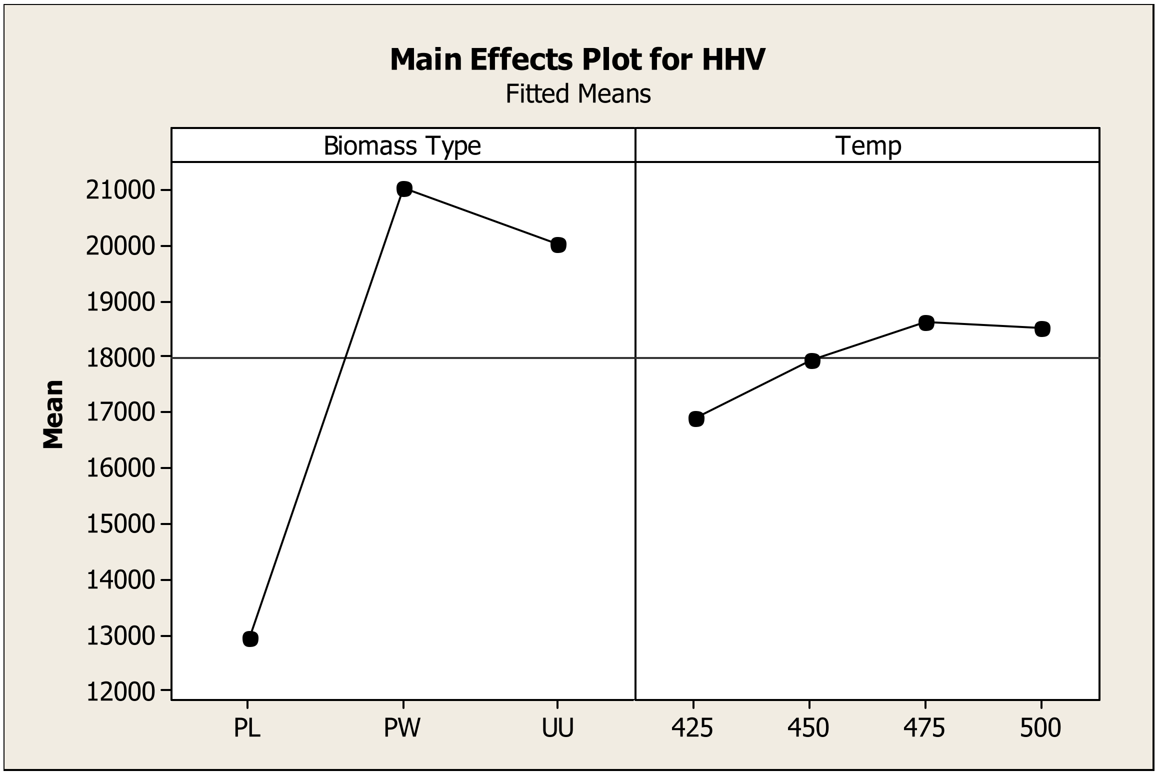
Unusual Observations for HHV

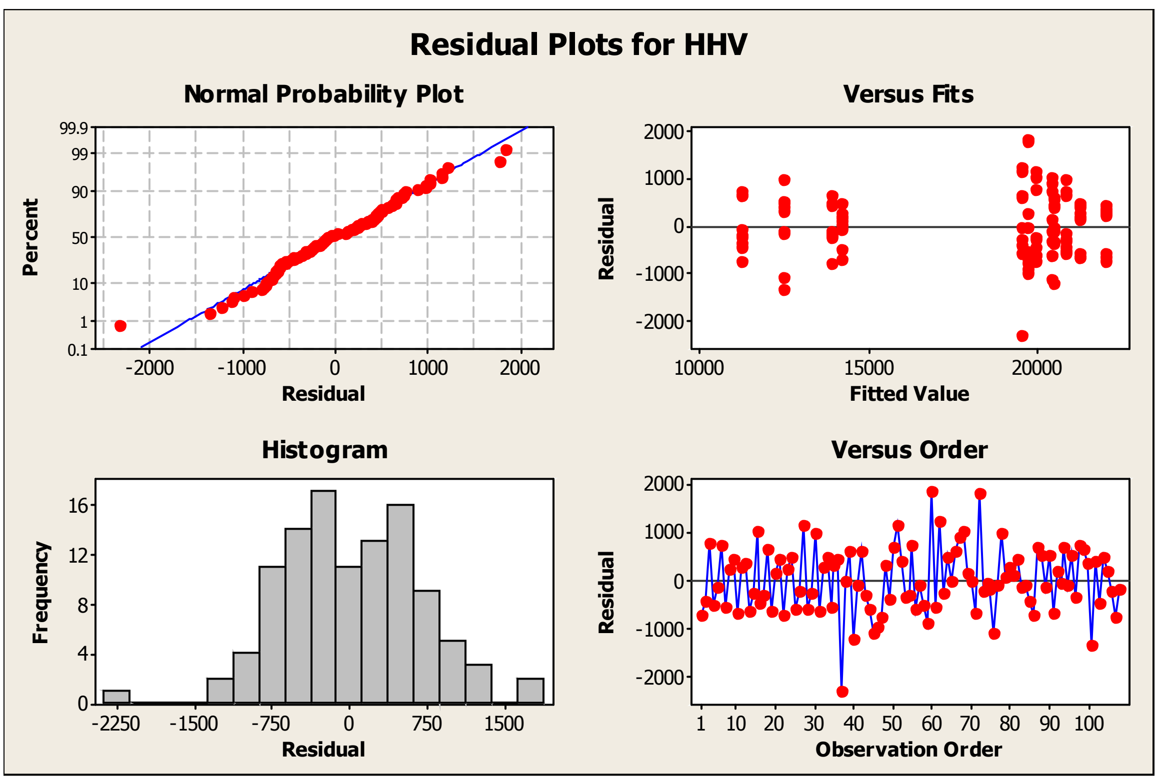
Obs	HHV	Fit	SE Fit	Residual	St Resid	
37	17210.0	19531.9	236.7	-2321.9	-3.47	R
60	21532.0	19685.8	236.7	1846.2	2.76	R
72	21471.0	19685.8	236.7	1785.2	2.67	R

```
101  11109.0  12467.0   236.7   -1358.0     -2.03 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable HHV
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass
Type     Lower  Center  Upper  -----+---------+---------+---------+-
PW        7684    8083   8482                                 (*)
UU        6701    7100   7499                             (-*)
                               -----+---------+---------+---------+-
                                    0      3000      6000      9000

Biomass Type = PW  subtracted from:

Biomass
Type     Lower  Center   Upper  -----+---------+---------+---------+-
UU       -1382  -983.0  -584.2  (-*)
                                -----+---------+---------+---------+-
                                     0      3000      6000      9000
Tukey Simultaneous Tests
Response Variable HHV
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
PW             8083       167.4    48.29    0.0000
UU             7100       167.4    42.42    0.0000

Biomass Type = PW  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
UU           -983.0       167.4   -5.873    0.0000

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable HHV
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

Temp   Lower  Center  Upper  -------+---------+---------+---------
450    538.6    1044   1550               (-----*-----)
475   1219.8    1725   2231                       (------*-----)
500   1133.7    1639   2145                      (-----*------)
                             -------+---------+---------+---------
                                    0       800      1600

Temp = 450  subtracted from:

Temp   Lower  Center  Upper  -------+---------+---------+---------
475   175.64   681.3   1187          (------*-----)
500    89.49   595.1   1101         (-----*------)
                             -------+---------+---------+---------
                                    0       800      1600


Temp = 475  subtracted from:
```

```
Temp   Lower  Center  Upper  -------+---------+---------+---------
500   -591.8  -86.15  419.5  (-----*-----)
                             -------+---------+---------+---------
                                    0       800      1600


Tukey Simultaneous Tests
Response Variable HHV
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
450         1044       193.3    5.403    0.0000
475         1725       193.3    8.928    0.0000
500         1639       193.3    8.482    0.0000


Temp = 450  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
475        681.3       193.3    3.525    0.0036
500        595.1       193.3    3.079    0.0142


Temp = 475  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
500       -86.15       193.3  -0.4458    0.9703
```




Main Effects Plot for HHV
Fitted Means
Biomass Type
Temp
Mean
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
PL
PW
UU
425
450
475
500


Residual Plots for HHV
Normal Probability Plot
Versus Fits
Percent
Residual
Fitted Value
Histogram
Versus Order
Frequency
Observation Order

Minitab worksheet for solid content of bio-oil:

Biomass Type	Temp	Solid	Biomass Type	Temp	Solid	Biomass Type	Temp	Solid
PW	425	0.582037	UU	425	0.392927	PL	425	0.086999
PW	425	0.53	UU	425	0.246427	PL	425	0.129122
PW	425	0.769538	UU	425	0.279034	PL	425	0.069156
PW	450	0.470035	UU	450	0.464058	PL	450	0.107885
PW	450	0.571372	UU	450	0.35308	PL	450	0.165402
PW	450	0.587555	UU	450	0.433401	PL	450	0.097865
PW	475	0.79602	UU	475	0.538833	PL	475	0.15086
PW	475	0.712637	UU	475	0.503803	PL	475	0.203149
PW	475	0.57614	UU	475	0.613376	PL	475	0.336168
PW	500	0.226267	UU	500	0.487417	PL	500	0.099246
PW	500	0.66521	UU	500	0.49635	PL	500	0.142126
PW	500	0.817629	UU	500	0.470871	PL	500	0.208499
PW	425	0.584158	UU	425	0.49829	PL	425	0.09
PW	425	0.607267	UU	425	0.188268	PL	425	0.149686
PW	425	0.729635	UU	425	0.214467	PL	425	0.088652
PW	450	0.501205	UU	450	0.520884	PL	450	0.11919
PW	450	0.520067	UU	450	0.347222	PL	450	0.183274
PW	450	0.607509	UU	450	0.500093	PL	450	0.110909
PW	475	0.76137	UU	475	0.452358	PL	475	0.185203
PW	475	0.651172	UU	475	0.485918	PL	475	0.238592
PW	475	0.574656	UU	475	0.631497	PL	475	0.378185
PW	500	0.26973	UU	500	0.553852	PL	500	0.13911
PW	500	0.74859	UU	500	0.5	PL	500	0.156571
PW	500	0.847965	UU	500	0.557894	PL	500	0.235594
PW	425	0.525898	UU	425	0.411967	PL	425	0.079554
PW	425	0.598444	UU	425	0.13	PL	425	0.125337
PW	425	0.766052	UU	425	0.192608	PL	425	0.110876
PW	450	0.491932	UU	450	0.395531	PL	450	0.130208
PW	450	0.591601	UU	450	0.406622	PL	450	0.183185
PW	450	0.628366	UU	450	0.409222	PL	450	0.119868
PW	475	0.8	UU	475	0.516006	PL	475	0.195446
PW	475	0.469812	UU	475	0.454905	PL	475	0.235548
PW	475	0.569317	UU	475	0.584795	PL	475	0.348814
PW	500	0.290174	UU	500	0.427388	PL	500	0.148559
PW	500	0.713412	UU	500	0.553367	PL	500	0.176956
PW	500	0.759568	UU	500	0.544806	PL	500	0.257834

Minitab result for solid content of bio-oil:

Two-way ANOVA: Solid versus Biomass Type, Temp

```
Source         DF       SS       MS       F      P
Biomass Type    2  3.58458  1.79229  168.89  0.000
Temp            3  0.30983  0.10328    9.73  0.000
Interaction     6  0.19942  0.03324    3.13  0.008
Error          96  1.01878  0.01061
Total         107  5.11261

S = 0.1030   R-Sq = 80.07%   R-Sq(adj) = 77.79%


                   Individual 95% CIs For Mean Based on
Biomass            Pooled StDev
Type         Mean  -+---------+---------+---------+--------
PL       0.166212  (-*-)
PW       0.608676                               (--*-)
UU       0.437709                  (-*-)
                   -+---------+---------+---------+--------
                   0.15      0.30      0.45      0.60


                Individual 95% CIs For Mean Based on Pooled StDev
Temp      Mean    +---------+---------+---------+---------
425   0.339867    (------*-----)
450   0.371020         (------*-----)
475   0.480170                           (------*------)
500   0.425740                  (------*------)
                  +---------+---------+---------+---------
                0.300     0.360     0.420     0.480
```

General Linear Model: Solid versus Biomass Type, Temp

```
Factor        Type   Levels  Values
Biomass Type  fixed       3  PL, PW, UU
Temp          fixed       4  425, 450, 475, 500


Analysis of Variance for Solid, using Adjusted SS for Tests

Source              DF   Seq SS   Adj SS   Adj MS       F      P
Biomass Type         2  3.58458  3.58458  1.79229  168.89  0.000
Temp                 3  0.30983  0.30983  0.10328    9.73  0.000
Biomass Type*Temp    6  0.19942  0.19942  0.03324    3.13  0.008
Error               96  1.01878  1.01878  0.01061
Total              107  5.11261


S = 0.103016   R-Sq = 80.07%   R-Sq(adj) = 77.79%


Unusual Observations for Solid

Obs     Solid       Fit    SE Fit   Residual  St Resid
 10  0.226267  0.593172  0.034339  -0.366905     -3.78 R
 12  0.817629  0.593172  0.034339   0.224457      2.31 R
 22  0.269730  0.593172  0.034339  -0.323441     -3.33 R
 24  0.847965  0.593172  0.034339   0.254793      2.62 R
```

```
 34  0.290174  0.593172  0.034339  -0.302998     -3.12 R
 49  0.498290  0.283776  0.034339   0.214514      2.21 R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Solid
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass
Type      Lower  Center   Upper    -+---------+---------+---------+-----
PW       0.3846  0.4425  0.5003                                (--*--)
UU       0.2136  0.2715  0.3294                        (--*-)
                                   -+---------+---------+---------+-----
                                 -0.20      0.00      0.20      0.40
Biomass Type = PW  subtracted from:

Biomass
Type       Lower   Center    Upper    -+---------+---------+---------+-----
UU       -0.2288  -0.1710  -0.1131    (-*--)
                                      -+---------+---------+---------+-----
                                    -0.20      0.00      0.20      0.40
Tukey Simultaneous Tests
Response Variable Solid
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
PW           0.4425     0.02428    18.22    0.0000
UU           0.2715     0.02428    11.18    0.0000

Biomass Type = PW  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
UU          -0.1710     0.02428   -7.041    0.0000

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Solid
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

Temp     Lower   Center   Upper  ---+---------+---------+---------+---
450   -0.04220  0.03115  0.1045          (------*------)
475    0.06695  0.14030  0.2137                     (------*------)
500    0.01252  0.08587  0.1592               (-------*------)
                                 ---+---------+---------+---------+---
                                 -0.10      0.00      0.10      0.20


Temp = 450  subtracted from:

Temp     Lower   Center   Upper  ---+---------+---------+---------+---
475    0.03580  0.10915  0.1825                  (------*-------)
500   -0.01863  0.05472  0.1281            (------*-------)
                                 ---+---------+---------+---------+---
                                 -0.10      0.00      0.10      0.20


Temp = 475  subtracted from:
```

```
Temp    Lower    Center    Upper   ---+---------+---------+---------+---
500   -0.1278  -0.05443  0.01892  (-------*------)
                                   ---+---------+---------+---------+---
                                   -0.10      0.00      0.10      0.20
```

Tukey Simultaneous Tests
Response Variable Solid
All Pairwise Comparisons among Levels of Temp
Temp = 425 subtracted from:

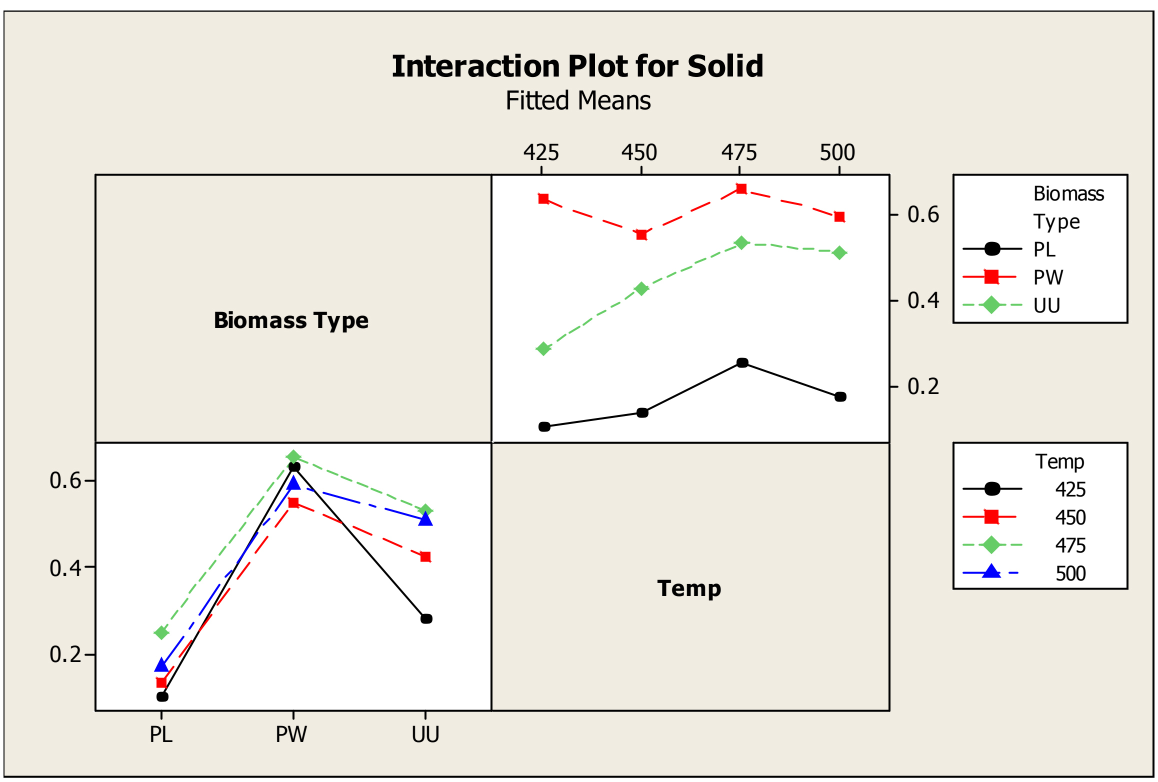
Temp	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
450	0.03115	0.02804	1.111	0.6836
475	0.14030	0.02804	5.004	0.0000
500	0.08587	0.02804	3.063	0.0149

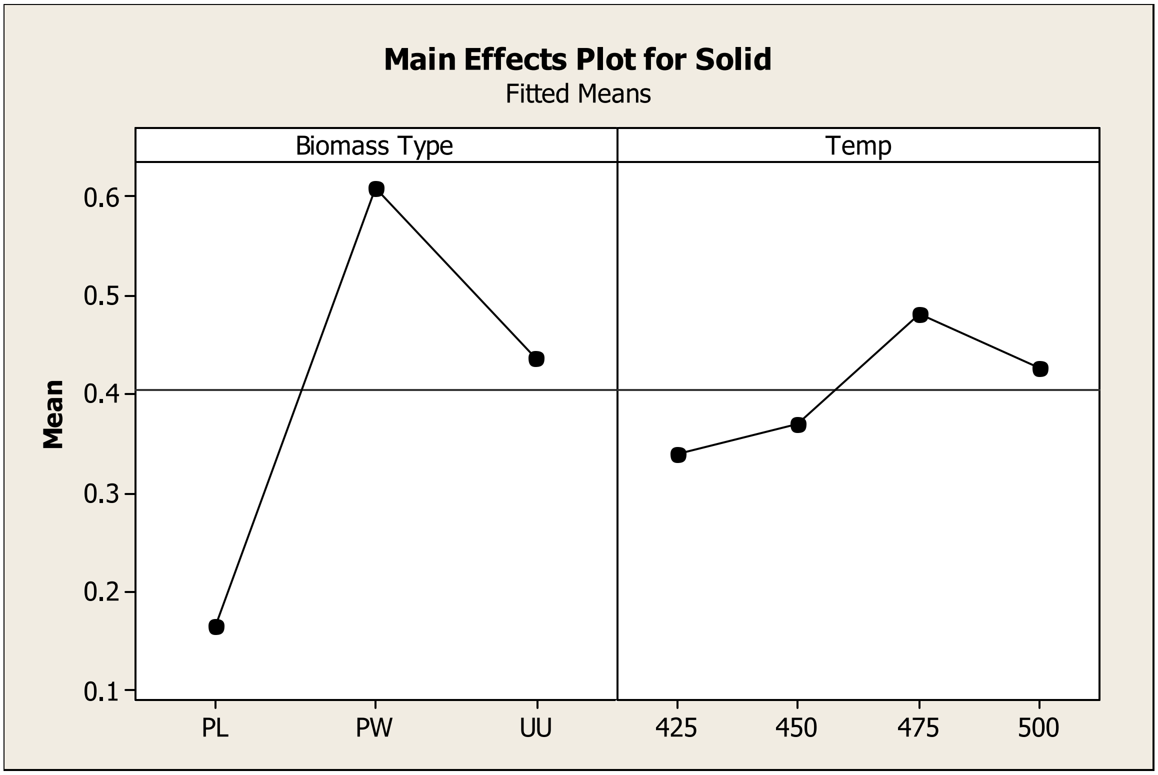
Temp = 450 subtracted from:

Temp	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
475	0.10915	0.02804	3.893	0.0010
500	0.05472	0.02804	1.952	0.2138

Temp = 475 subtracted from:

Temp	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
500	-0.05443	0.02804	-1.941	0.2179




Main Effects Plot for Solid
Fitted Means
Biomass Type
Temp
Mean
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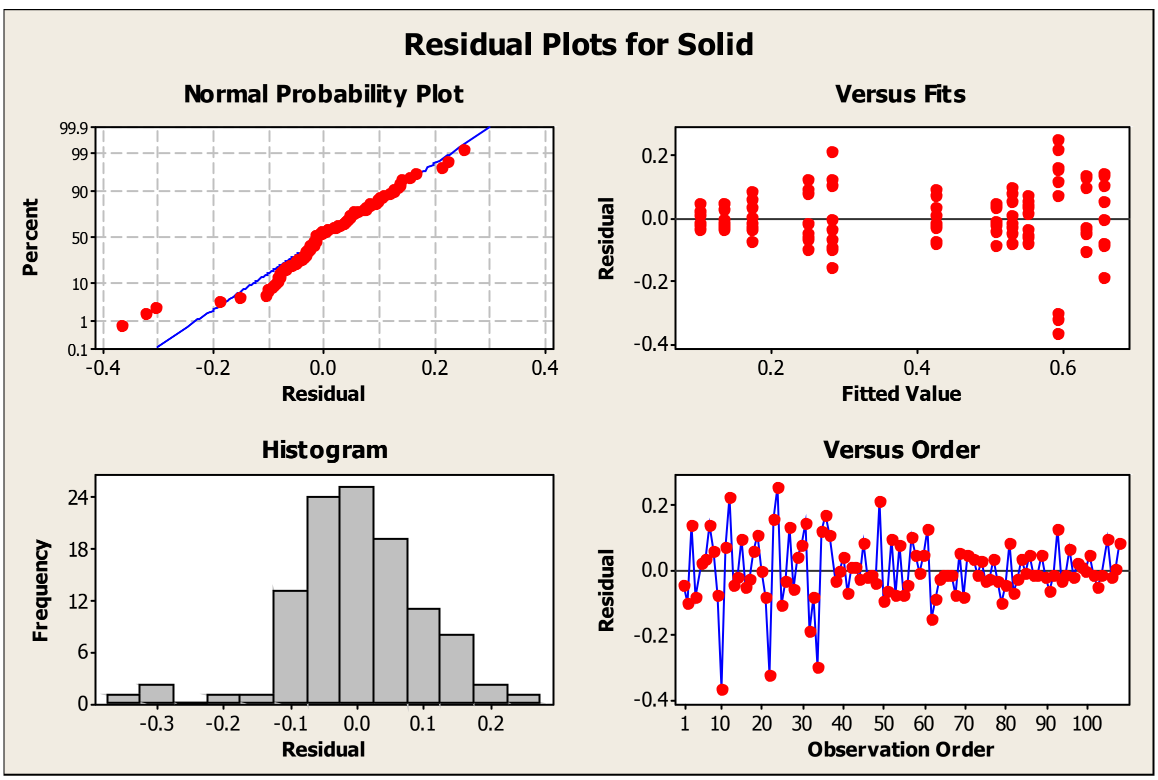
0.5
0.4
0.3
0.2
0.1
PL
PW
UU
425
450
475
500


Residual Plots for Solid
Normal Probability Plot
Percent
Residual
Versus Fits
Residual
Fitted Value
Histogram
Frequency
Residual
Versus Order
Residual
Observation Order

Minitab worksheet for ash content in bio-oil:

Biomass Type	Temp	Ash	Biomass Type	Temp	Ash	Biomass Type	Temp	Ash
PW	425	0.480725	UU	425	1.32812	PL	425	0.089557
PW	425	0.563693	UU	425	0.919414	PL	425	0.127944
PW	425	0.805639	UU	425	0.836517	PL	425	0.095102
PW	450	0.749115	UU	450	0.813623	PL	450	0.142401
PW	450	1.294919	UU	450	0.834873	PL	450	0.182567
PW	450	0.974252	UU	450	0.47838	PL	450	0.185048
PW	475	1.07902	UU	475	0.964915	PL	475	0.201911
PW	475	0.730417	UU	475	0.872886	PL	475	0.202807
PW	475	0.811784	UU	475	0.980157	PL	475	0.184944
PW	500	0.196056	UU	500	0.680418	PL	500	0.137915
PW	500	0.35865	UU	500	0.574592	PL	500	0.157347
PW	500	0.426169	UU	500	0.498069	PL	500	0.132626
PW	425	0.485051	UU	425	1.344185	PL	425	0.092769
PW	425	0.551702	UU	425	0.829388	PL	425	0.105313
PW	425	0.815747	UU	425	0.628008	PL	425	0.0825
PW	450	0.858663	UU	450	0.885836	PL	450	0.15015
PW	450	1.257584	UU	450	0.73781	PL	450	0.19114
PW	450	0.980428	UU	450	0.466871	PL	450	0.172393
PW	475	0.955481	UU	475	1.243104	PL	475	0.196446
PW	475	0.756023	UU	475	0.867419	PL	475	0.209678
PW	475	0.844245	UU	475	1.137171	PL	475	0.224286
PW	500	0.186827	UU	500	0.727325	PL	500	0.130915
PW	500	0.374152	UU	500	0.727917	PL	500	0.162063
PW	500	0.43956	UU	500	0.420205	PL	500	0.143685
PW	425	0.446429	UU	425	0.819854	PL	425	0.112428
PW	425	0.546555	UU	425	0.948976	PL	425	0.117592
PW	425	0.793595	UU	425	0.677721	PL	425	0.075146
PW	450	0.826187	UU	450	0.944852	PL	450	0.135403
PW	450	1.186333	UU	450	0.682161	PL	450	0.182855
PW	450	0.905099	UU	450	0.544433	PL	450	0.170986
PW	475	0.944025	UU	475	1.306687	PL	475	0.197157
PW	475	0.759235	UU	475	0.959295	PL	475	0.194246
PW	475	0.825848	UU	475	1.230258	PL	475	0.198042
PW	500	0.211202	UU	500	0.765703	PL	500	0.134797
PW	500	0.336159	UU	500	0.692345	PL	500	0.174706
PW	500	0.452621	UU	500	0.518408	PL	500	0.145609

Minitab result for ash content in bio-oil:

Two-way ANOVA: Ash.oil versus Biomass Type, Temp

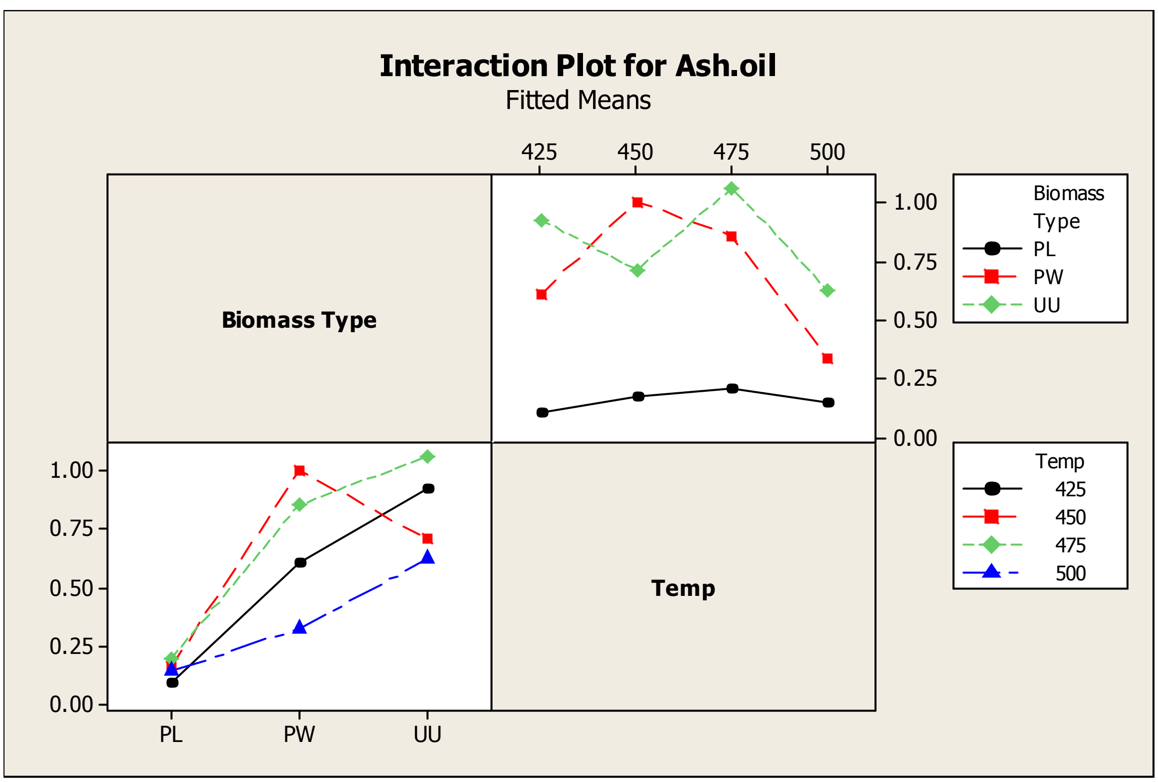
```
Source         DF       SS       MS       F      P
Biomass Type    2   9.2736  4.63679  244.94  0.000
Temp            3   1.7146  0.57152   30.19  0.000
Interaction     6   1.7653  0.29422   15.54  0.000
Error          96   1.8173  0.01893
Total         107  14.5708

S = 0.1376   R-Sq = 87.53%   R-Sq(adj) = 86.10%


                   Individual 95% CIs For Mean Based on
Biomass            Pooled StDev
Type         Mean  -----+---------+---------+---------+----
PL       0.153902  (--*-)
PW       0.700255                             (-*-)
UU       0.830219                                   (--*-)
                   -----+---------+---------+---------+----
                      0.20      0.40      0.60      0.80

                Individual 95% CIs For Mean Based on
                Pooled StDev
Temp      Mean  ----+---------+---------+---------+-----
425   0.545173               (---*----)
450   0.627199                      (---*----)
475   0.706574                             (---*---)
500   0.366890  (----*---)
                ----+---------+---------+---------+-----
                  0.36      0.48      0.60      0.72
```

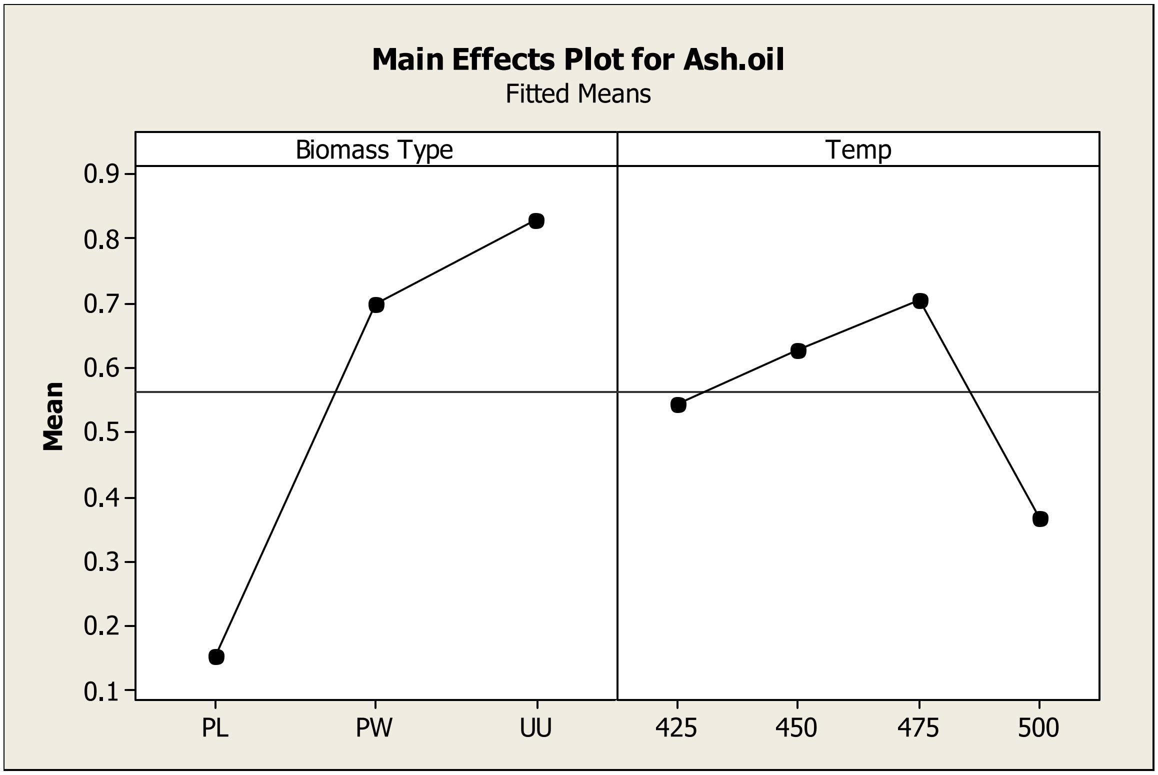
General Linear Model: Ash.oil versus Biomass Type, Temp

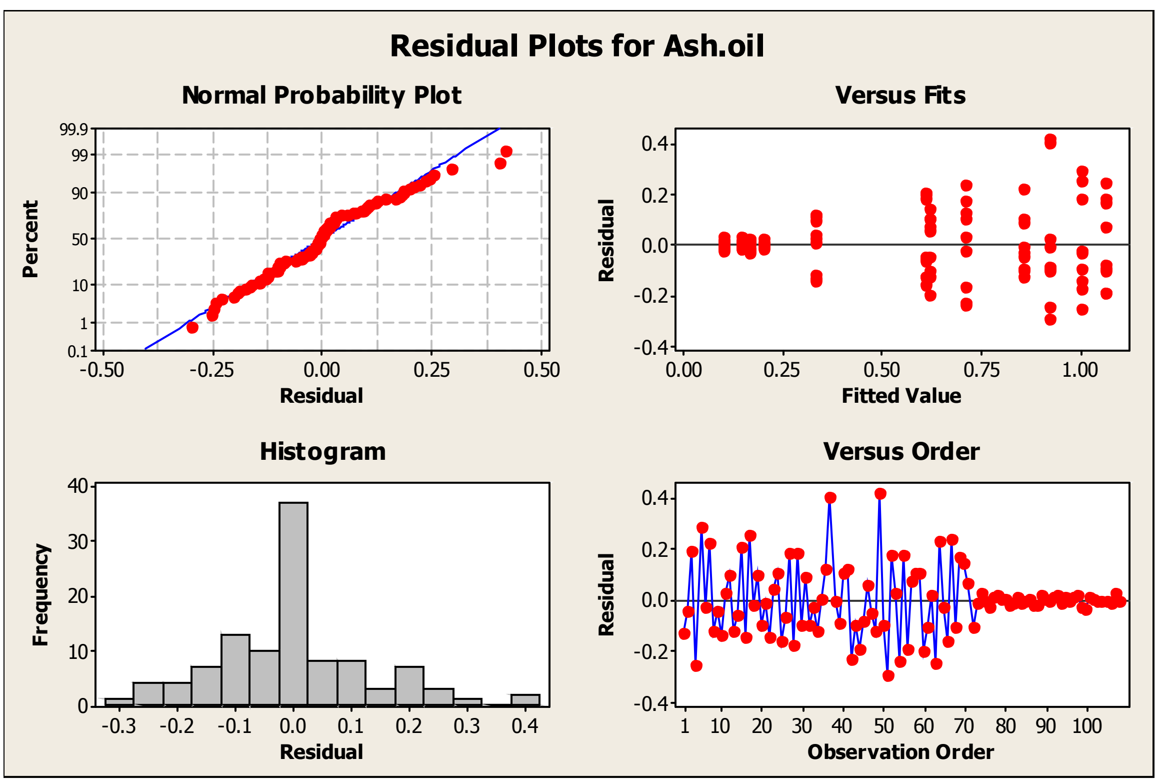
```
Factor        Type   Levels  Values
Biomass Type  fixed       3  PL, PW, UU
Temp          fixed       4  425, 450, 475, 500

Analysis of Variance for Ash.oil, using Adjusted SS for Tests

Source              DF   Seq SS   Adj SS   Adj MS       F      P
Biomass Type         2   9.2736   9.2736   4.6368  244.94  0.000
Temp                 3   1.7146   1.7146   0.5715   30.19  0.000
Biomass Type*Temp    6   1.7653   1.7653   0.2942   15.54  0.000
Error               96   1.8173   1.8173   0.0189
Total              107  14.5708

S = 0.137589   R-Sq = 87.53%   R-Sq(adj) = 86.10%


Unusual Observations for Ash.oil

Obs  Ash.oil      Fit   SE Fit  Residual  St Resid
  5  1.29492  1.00362  0.04586   0.29130      2.25 R
 37  1.32812  0.92580  0.04586   0.40232      3.10 R
 49  1.34419  0.92580  0.04586   0.41839      3.23 R
 51  0.62801  0.92580  0.04586  -0.29779     -2.30 R

R denotes an observation with a large standardized residual.
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Ash.oil
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass
Type      Lower  Center   Upper  -------+---------+---------+---------
PW       0.4691  0.5464  0.6236                    (---*---)
UU       0.5990  0.6763  0.7536                             (---*---)
                                 -------+---------+---------+---------
                                      0.20      0.40      0.60
Biomass Type = PW  subtracted from:

Biomass
Type       Lower  Center   Upper  -------+---------+---------+---------
UU       0.05269  0.1300  0.2072  (--*---)
                                  -------+---------+---------+---------
                                       0.20      0.40      0.60


Tukey Simultaneous Tests
Response Variable Ash.oil
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
PW           0.5464     0.03243    16.85    0.0000
UU           0.6763     0.03243    20.85    0.0000


Biomass Type = PW  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
UU           0.1300     0.03243    4.008    0.0004


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Ash.oil
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

Temp    Lower   Center     Upper   --+---------+---------+---------+----
450   -0.0159   0.0820   0.18000                      (----*----)
475    0.0634   0.1614   0.25937                          (----*----)
500   -0.2763  -0.1783  -0.08031          (----*----)
                                   --+---------+---------+---------+----
                                 -0.40     -0.20     -0.00      0.20


Temp = 450  subtracted from:

Temp    Lower   Center    Upper   --+---------+---------+---------+----
475   -0.0186   0.0794   0.1773                      (----*----)
500   -0.3583  -0.2603  -0.1623       (----*----)
                                  --+---------+---------+---------+----
                                -0.40     -0.20     -0.00      0.20


Temp = 475  subtracted from:
```

```
Temp     Lower   Center    Upper   --+---------+---------+---------+----
500   -0.4377  -0.3397  -0.2417    (----*----)
                                   --+---------+---------+---------+----
                                 -0.40     -0.20     -0.00      0.20


Tukey Simultaneous Tests
Response Variable Ash.oil
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
450       0.0820     0.03745    2.190     0.1333
475       0.1614     0.03745    4.310     0.0002
500      -0.1783     0.03745   -4.761     0.0000


Temp = 450  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
475       0.0794     0.03745    2.120     0.1542
500      -0.2603     0.03745   -6.951     0.0000


Temp = 475  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
500      -0.3397     0.03745   -9.071     0.0000
```




Main Effects Plot for Ash.oil
Fitted Means
Biomass Type
Temp
Mean
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
PL
PW
UU
425
450
475
500


Residual Plots for Ash.oil
Normal Probability Plot
Percent
Residual
Versus Fits
Residual
Fitted Value
Histogram
Frequency
Residual
Versus Order
Residual
Observation Order

Minitab worksheet for water content in bio-oil:

Biomass Type	Temp	Water	Biomass Type	Temp	Water	Biomass Type	Temp	Water
PW	425	19.7133	UU	425	16.9154	PL	425	38.2552
PW	425	16.6584	UU	425	18.4162	PL	425	35.3269
PW	425	17.9501	UU	425	16.4609	PL	425	36.1420
PW	450	17.9856	UU	450	20.3106	PL	450	32.4739
PW	450	21.5228	UU	450	19.2539	PL	450	33.2167
PW	450	20.9411	UU	450	20.7650	PL	450	32.7847
PW	475	20.1805	UU	475	17.2414	PL	475	37.9976
PW	475	20.1176	UU	475	18.8261	PL	475	33.0142
PW	475	22.1117	UU	475	15.5316	PL	475	34.6171
PW	500	22.3072	UU	500	18.8889	PL	500	34.4727
PW	500	19.4704	UU	500	18.7266	PL	500	33.9004
PW	500	20.5381	UU	500	16.4900	PL	500	30.5182
PW	425	18.7135	UU	425	19.3939	PL	425	27.8173
PW	425	17.2584	UU	425	17.3010	PL	425	28.4452
PW	425	18.9064	UU	425	18.6916	PL	425	28.4275
PW	450	19.6079	UU	450	19.8087	PL	450	29.6718
PW	450	18.4308	UU	450	15.1515	PL	450	32.0700
PW	450	18.1951	UU	450	17.9806	PL	450	31.4490
PW	475	19.8886	UU	475	18.1664	PL	475	31.6967
PW	475	17.4872	UU	475	16.4794	PL	475	29.2430
PW	475	17.3250	UU	475	16.7264	PL	475	28.3048
PW	500	19.3603	UU	500	14.5903	PL	500	29.4547
PW	500	20.0976	UU	500	17.4292	PL	500	26.7702
PW	500	18.4775	UU	500	17.6707	PL	500	28.3817
PW	425	16.9205	UU	425	19.7664	PL	425	26.8384
PW	425	17.4978	UU	425	17.5757	PL	425	29.6718
PW	425	18.4462	UU	425	18.1043	PL	425	32.2360
PW	450	19.2012	UU	450	18.0023	PL	450	28.6307
PW	450	19.8886	UU	450	18.3259	PL	450	31.9990
PW	450	22.1589	UU	450	16.2429	PL	450	30.4163
PW	475	20.0037	UU	475	16.4948	PL	475	25.7493
PW	475	19.3799	UU	475	18.6255	PL	475	30.1772
PW	475	18.6220	UU	475	17.8282	PL	475	27.3222
PW	500	19.2818	UU	500	17.5438	PL	500	28.0163
PW	500	18.8679	UU	500	16.5145	PL	500	29.2100
PW	500	14.7656	UU	500	18.7097	PL	500	30.3428

Minitab worksheet for water content in bio-oil:

Two-way ANOVA: Water versus Biomass Type, Temp

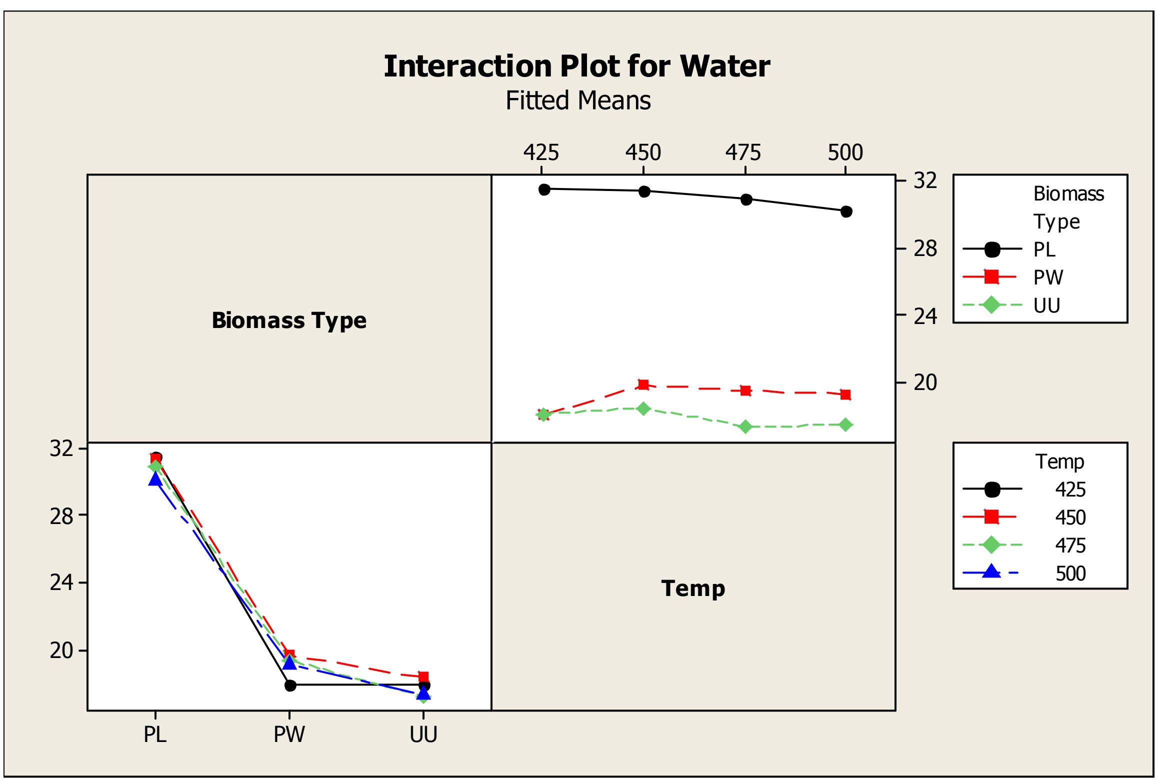
```
Source         DF       SS       MS       F      P
Biomass Type    2  3788.56  1894.28  387.23  0.000
Temp            3    13.23     4.41    0.90  0.444
Interaction     6    21.08     3.51    0.72  0.636
Error          96   469.62     4.89
Total         107  4292.49

S = 2.212   R-Sq = 89.06%   R-Sq(adj) = 87.81%


                  Individual 95% CIs For Mean Based on
Biomass           Pooled StDev
Type        Mean  -------+---------+---------+---------+--
PL       30.9739                                    (*-)
PW       19.1189     (-*-)
UU       17.8042  (-*)
                  -------+---------+---------+---------+--
                      20.0      24.0      28.0      32.0


               Individual 95% CIs For Mean Based on
               Pooled StDev
Temp     Mean  ----+---------+---------+---------+-----
425   22.5130      (-----------*-----------)
450   23.2032               (-----------*------------)
475   22.5614      (-----------*-----------)
500   22.2517  (-----------*-----------)
               ----+---------+---------+---------+-----
                21.70     22.40     23.10     23.80
```

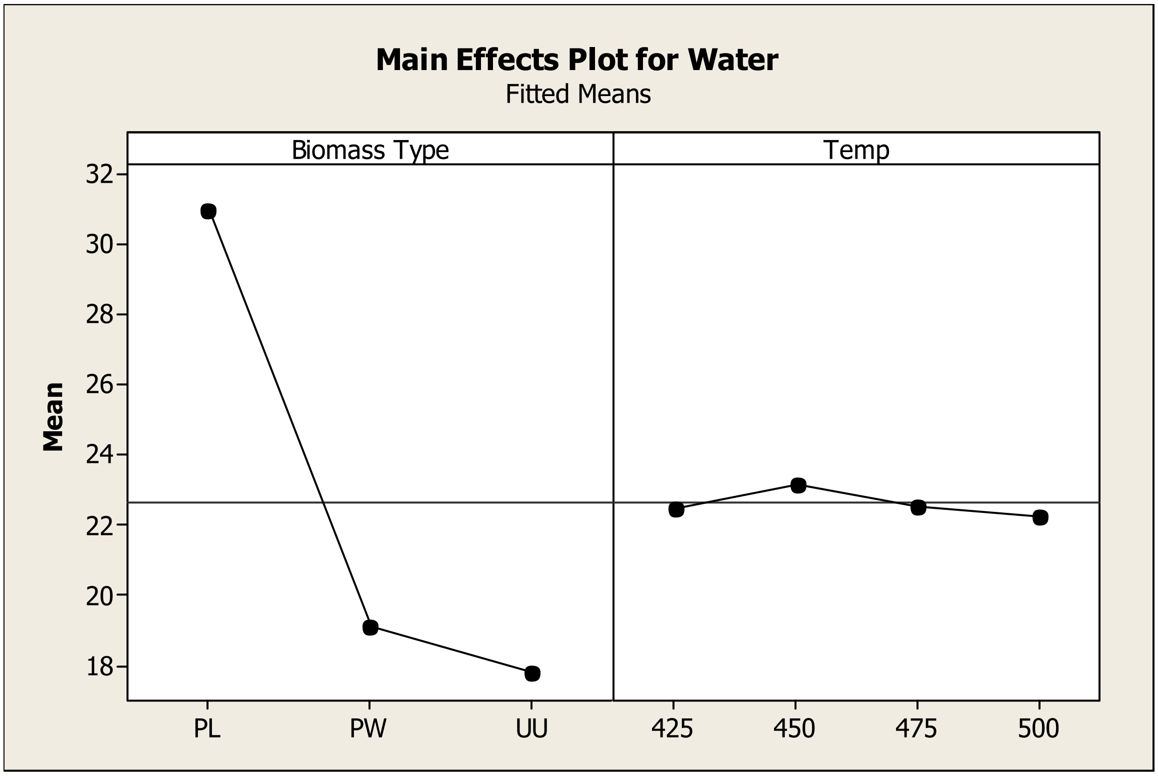
General Linear Model: Water versus Biomass Type, Temp

```
Factor        Type   Levels  Values
Biomass Type  fixed       3  PL, PW, UU
Temp          fixed       4  425, 450, 475, 500


Analysis of Variance for Water, using Adjusted SS for Tests

Source              DF   Seq SS   Adj SS   Adj MS       F      P
Biomass Type         2  3788.56  3788.56  1894.28  387.23  0.000
Temp                 3    13.23    13.23     4.41    0.90  0.444
Biomass Type*Temp    6    21.08    21.08     3.51    0.72  0.636
Error               96   469.62   469.62     4.89
Total              107  4292.49


S = 2.21176   R-Sq = 89.06%   R-Sq(adj) = 87.81%


Unusual Observations for Water

Obs    Water      Fit  SE Fit  Residual  St Resid
 36  14.7656  19.2407  0.7373   -4.4751     -2.15 R
 73  38.2552  31.4623  0.7373    6.7929      3.26 R
 75  36.1420  31.4623  0.7373    4.6797      2.24 R
```

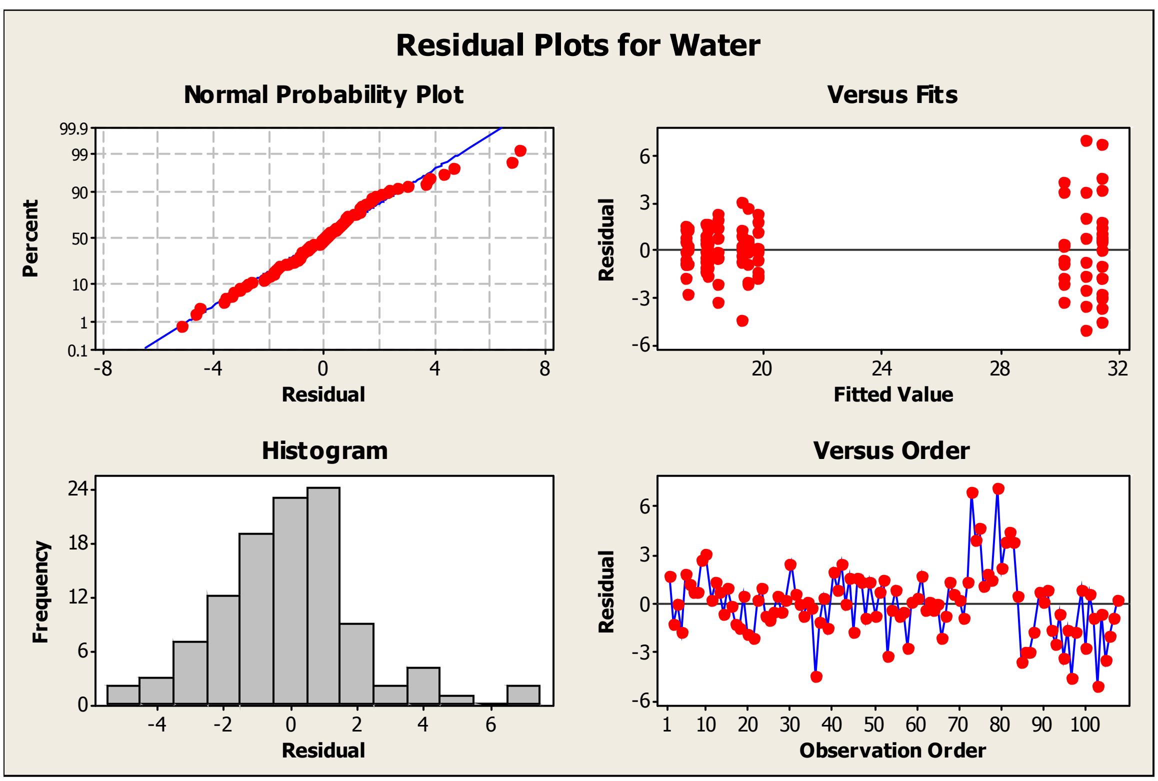
```
 79  37.9976  30.9025  0.7373    7.0952      3.40 R
 82  34.4727  30.1186  0.7373    4.3541      2.09 R
 97  26.8384  31.4623  0.7373   -4.6238     -2.22 R
103  25.7493  30.9025  0.7373   -5.1531     -2.47 R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Water
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass
Type      Lower  Center   Upper  ------+---------+---------+---------+
PW       -13.10  -11.86  -10.61     (--*--)
UU       -14.41  -13.17  -11.93  (--*--)
                                 ------+---------+---------+---------+
                                   -12.0      -8.0      -4.0       0.0

Biomass Type = PW  subtracted from:

Biomass
Type      Lower  Center     Upper  ------+---------+---------+---------+
UU       -2.557  -1.315  -0.07241                               (--*--)
                                   ------+---------+---------+---------+
                                     -12.0      -8.0      -4.0       0.0
Tukey Simultaneous Tests
Response Variable Water
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
PW           -11.86      0.5213   -22.74    0.0000
UU           -13.17      0.5213   -25.26    0.0000

Biomass Type = PW  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
UU           -1.315      0.5213   -2.522    0.0352


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Water
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

Temp   Lower   Center  Upper  -------+---------+---------+---------
450   -0.885   0.6902  2.265             (----------*---------)
475   -1.526   0.0484  1.623         (---------*----------)
500   -1.836  -0.2612  1.314       (---------*----------)
                              -------+---------+---------+---------
                                  -1.5       0.0       1.5


Temp = 450  subtracted from:

Temp   Lower   Center   Upper  -------+---------+---------+---------
475   -2.217  -0.6418  0.9332    (----------*---------)
500   -2.526  -0.9514  0.6235  (----------*---------)
                               -------+---------+---------+---------
                                   -1.5       0.0       1.5
```

```
Temp = 475  subtracted from:

Temp   Lower   Center  Upper  -------+---------+---------+---------
500   -1.885  -0.3097  1.265      (----------*---------)
                              -------+---------+---------+---------
                                    -1.5       0.0       1.5


Tukey Simultaneous Tests
Response Variable Water
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

      Difference       SE of             Adjusted
Temp    of Means  Difference  T-Value     P-Value
450       0.6902      0.6020   1.1466      0.6617
475       0.0484      0.6020   0.0805      0.9998
500      -0.2612      0.6020  -0.4340      0.9725

Temp = 450  subtracted from:

      Difference       SE of             Adjusted
Temp    of Means  Difference  T-Value     P-Value
475      -0.6418      0.6020   -1.066      0.7109
500      -0.9514      0.6020   -1.581      0.3945

Temp = 475  subtracted from:

      Difference       SE of             Adjusted
Temp    of Means  Difference  T-Value     P-Value
500      -0.3097      0.6020  -0.5144      0.9555
```





Main Effects Plot for Water
Fitted Means
Biomass Type
Temp
Mean
32
30
28
26
24
22
20
18
PL
PW
UU
425
450
475
500



Residual Plots for Water
Normal Probability Plot
Versus Fits
Histogram
Versus Order
Percent
Residual
Fitted Value
Frequency
Observation Order

Minitab worksheet for moisture content in biochar:

Biomass Type	Temp	Moisture	Biomass Type	Temp	Moisture	Biomass Type	Temp	Moisture
PW	425	2.8755	UU	425	1.4887	PL	425	4.0017
PW	425	2.7645	UU	425	1.4603	PL	425	3.0354
PW	425	2.6159	UU	425	1.5117	PL	425	2.4636
PW	450	2.9099	UU	450	1.2756	PL	450	3.7956
PW	450	3.2186	UU	450	0.8322	PL	450	2.6791
PW	450	2.9979	UU	450	0.6307	PL	450	1.5839
PW	475	2.9574	UU	475	0.8777	PL	475	4.2331
PW	475	2.9187	UU	475	1.7056	PL	475	3.2892
PW	475	3.4428	UU	475	1.0783	PL	475	2.1294
PW	500	3.4530	UU	500	1.2302	PL	500	4.4069
PW	500	4.1082	UU	500	1.5731	PL	500	3.9013
PW	500	3.3058	UU	500	0.5585	PL	500	2.7710
PW	425	2.8505	UU	425	1.1309	PL	425	3.8600
PW	425	2.8528	UU	425	0.3679	PL	425	2.9864
PW	425	2.6565	UU	425	0.9378	PL	425	2.3685
PW	450	3.0549	UU	450	0.2652	PL	450	3.8115
PW	450	3.1805	UU	450	0.3188	PL	450	2.2004
PW	450	3.3695	UU	450	0.0611	PL	450	1.5316
PW	475	2.9479	UU	475	0.2509	PL	475	4.5092
PW	475	2.9566	UU	475	0.7393	PL	475	3.4896
PW	475	4.2580	UU	475	0.5414	PL	475	2.3087
PW	500	3.4728	UU	500	0.0881	PL	500	4.5753
PW	500	3.8999	UU	500	1.0409	PL	500	3.7435
PW	500	3.5657	UU	500	0.1959	PL	500	2.7764
PW	425	2.7933	UU	425	1.4620	PL	425	3.9275
PW	425	2.7377	UU	425	0.7540	PL	425	2.9798
PW	425	2.7281	UU	425	1.1321	PL	425	2.5143
PW	450	3.2380	UU	450	1.0262	PL	450	3.7490
PW	450	3.0077	UU	450	0.6122	PL	450	2.7062
PW	450	3.2816	UU	450	0.0534	PL	450	1.4475
PW	475	3.0735	UU	475	0.3143	PL	475	4.3125
PW	475	3.1752	UU	475	0.8308	PL	475	3.0165
PW	475	4.0515	UU	475	0.5970	PL	475	2.1280
PW	500	3.6391	UU	500	0.3851	PL	500	4.5880
PW	500	3.8097	UU	500	1.2849	PL	500	3.6458
PW	500	3.5013	UU	500	1.1056	PL	500	2.7989

Minitab result for moisture content in biochar:

Two-way ANOVA: Moisture.char versus Biomass Type, Temp

Source	DF	SS	MS	F	P
Biomass Type	2	134.612	67.3059	199.04	0.000
Temp	3	5.255	1.7516	5.18	0.002
Interaction	6	5.193	0.8656	2.56	0.024
Error	96	32.463	0.3382		
Total	107	177.523			

```
S = 0.5815   R-Sq = 81.71%   R-Sq(adj) = 79.62%


Biomass           Individual 95% CIs For Mean Based on Pooled StDev
Type        Mean   -+---------+---------+---------+--------
PL       3.17405                                   (-*--)
PW       3.21307                                   (--*--)
UU       0.82551   (--*--)
                   -+---------+---------+---------+--------
                  0.70      1.40      2.10      2.80


               Individual 95% CIs For Mean Based on
               Pooled StDev
Temp     Mean  -------+---------+---------+---------+--
425   2.34287          (------*-------)
450   2.10514  (------*-------)
475   2.44938             (-------*------)
500   2.71945                      (-------*------)
               -------+---------+---------+---------+--
                    2.10      2.40      2.70      3.00
```

General Linear Model: Moisture.char versus Biomass Type, Temp

Factor	Type	Levels	Values
Biomass Type	fixed	3	PL, PW, UU
Temp	fixed	4	425, 450, 475, 500

Analysis of Variance for Moisture.char, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Biomass Type	2	134.612	134.612	67.306	199.04	0.000
Temp	3	5.255	5.255	1.752	5.18	0.002
Biomass Type*Temp	6	5.193	5.193	0.866	2.56	0.024
Error	96	32.463	32.463	0.338		
Total	107	177.523				

S = 0.581512   R-Sq = 81.71%   R-Sq(adj) = 79.62%

Unusual Observations for Moisture.char

Obs	Moisture.char	Fit	SE Fit	Residual	St Resid	
76	3.79563	2.61165	0.19384	1.18397	2.16	R
81	2.12944	3.26848	0.19384	-1.13904	-2.08	R
88	3.81152	2.61165	0.19384	1.19987	2.19	R
91	4.50921	3.26848	0.19384	1.24073	2.26	R
100	3.74903	2.61165	0.19384	1.13738	2.07	R
102	1.44748	2.61165	0.19384	-1.16417	-2.12	R
105	2.12796	3.26848	0.19384	-1.14052	-2.08	R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Moisture.char
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL subtracted from:

```
Biomass
Type      Lower  Center   Upper  -------+---------+---------+---------
PW       -0.288   0.039   0.366                       (--*---)
UU       -2.675  -2.349  -2.022  (---*--)
                                 -------+---------+---------+---------
                                     -2.0      -1.0       0.0
```

Biomass Type = PW subtracted from:

```
Biomass
Type      Lower  Center   Upper  -------+---------+---------+---------
UU       -2.714  -2.388  -2.061  (--*--)
                                 -------+---------+---------+---------
                                     -2.0      -1.0       0.0
```

Tukey Simultaneous Tests
Response Variable Moisture.char
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL subtracted from:

Biomass Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
PW	0.039	0.1371	0.28	0.9563
UU	-2.349	0.1371	-17.13	0.0000

Biomass Type = PW subtracted from:

Biomass Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
UU	-2.388	0.1371	-17.42	0.0000

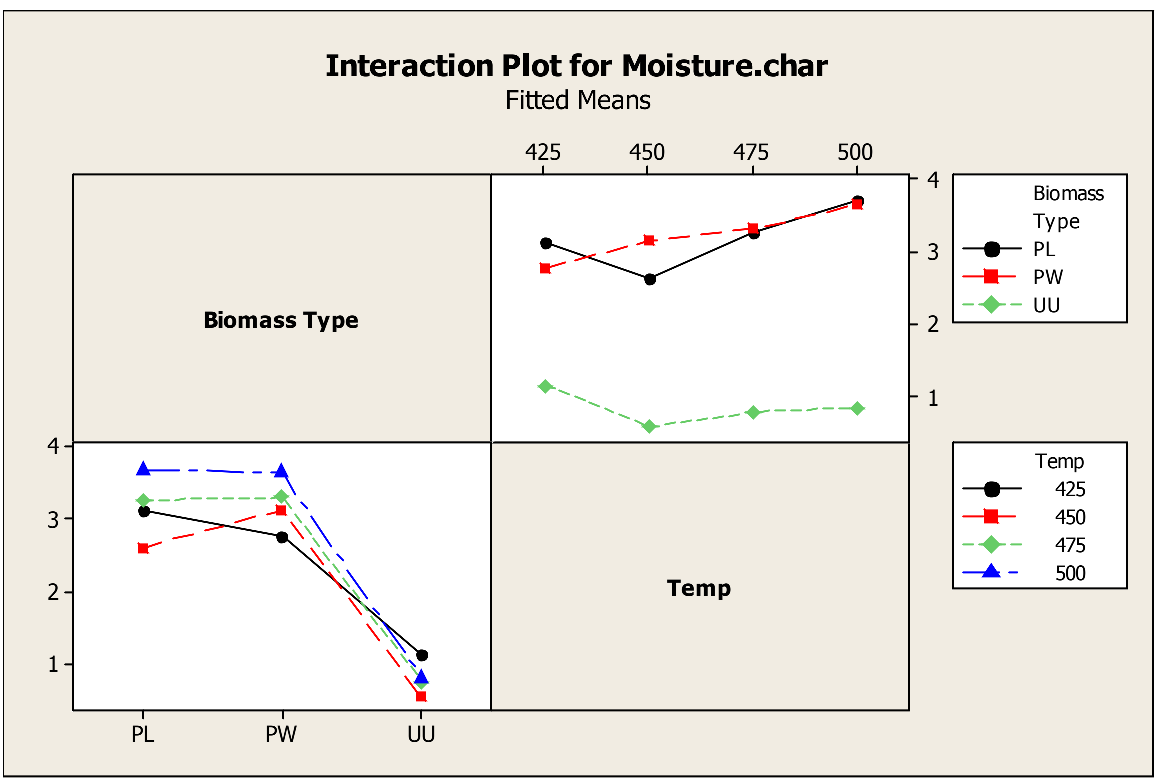
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Moisture.char
All Pairwise Comparisons among Levels of Temp
Temp = 425 subtracted from:

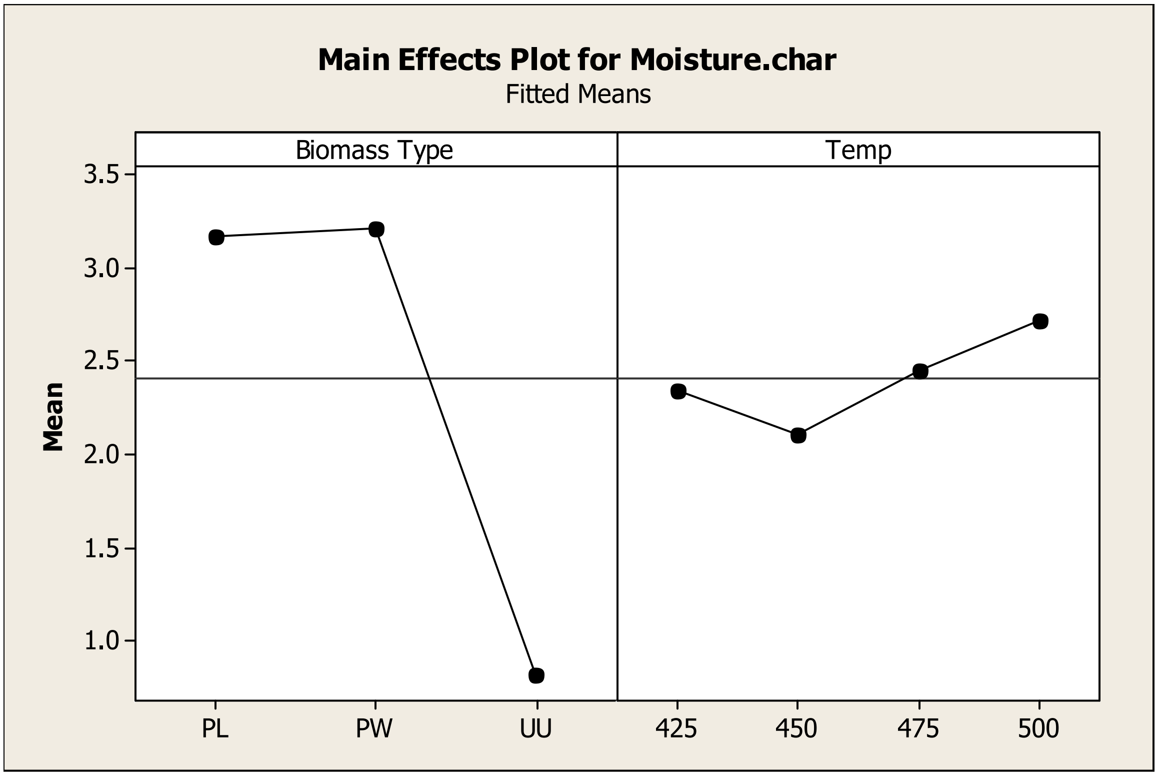
```
Temp    Lower   Center   Upper  ---+---------+---------+---------+---
450   -0.6518  -0.2377  0.1763  (-------*--------)
475   -0.3076   0.1065  0.5206         (-------*-------)
500   -0.0375   0.3766  0.7907              (--------*-------)
                                ---+---------+---------+---------+---
                                -0.50      0.00      0.50      1.00
```

Temp = 450 subtracted from:

```
Temp     Lower  Center   Upper  ---+---------+---------+---------+---
475   -0.06983  0.3442  0.7583            (-------*-------)
500    0.20024  0.6143  1.0284                 (-------*--------)
                                ---+---------+---------+---------+---
                                -0.50      0.00      0.50      1.00
```

```
Temp = 475  subtracted from:

Temp     Lower  Center   Upper   ---+---------+---------+---------+---
500   -0.1440  0.2701  0.6841              (-------*--------)
                                 ---+---------+---------+---------+---
                                 -0.50      0.00      0.50      1.00


Tukey Simultaneous Tests
Response Variable Moisture.char
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
450      -0.2377      0.1583   -1.502     0.4403
475       0.1065      0.1583    0.673     0.9071
500       0.3766      0.1583    2.379     0.0880


Temp = 450  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
475       0.3442      0.1583    2.175     0.1376
500       0.6143      0.1583    3.881     0.0011

Temp = 475  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
500       0.2701      0.1583    1.706     0.3260
```




Main Effects Plot for Moisture.char
Fitted Means
Biomass Type
Temp
Mean
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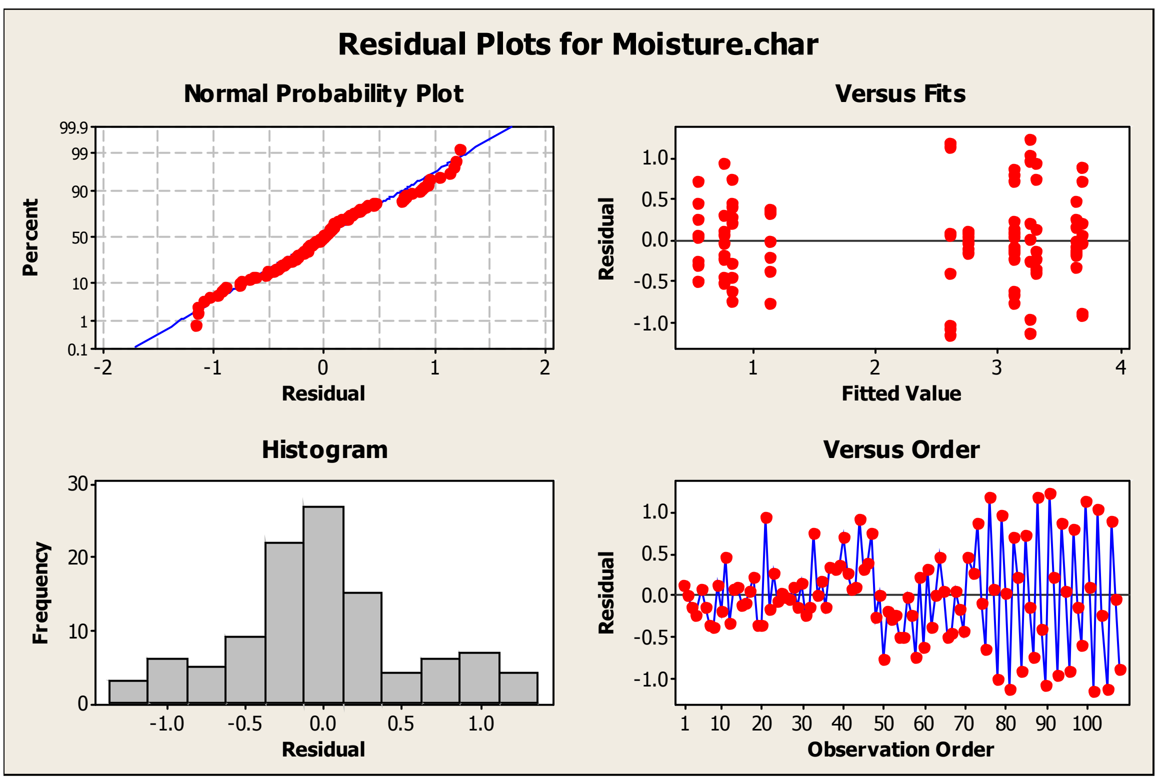
2.5
2.0
1.5
1.0
PL
PW
UU
425
450
475
500


Residual Plots for Moisture.char
Normal Probability Plot
Percent
Residual
Versus Fits
Residual
Fitted Value
Histogram
Frequency
Residual
Versus Order
Residual
Observation Order

Minitab worksheet for ash content in biochar:

Biomass Type	Temp	Ash	Biomass Type	Temp	Ash	Biomass Type	Temp	Ash
PW	425	0.5232	UU	425	2.3028	PL	425	52.7796
PW	425	0.7885	UU	425	1.7796	PL	425	40.5930
PW	425	0.7589	UU	425	1.8710	PL	425	47.2097
PW	450	0.8972	UU	450	2.1720	PL	450	54.5242
PW	450	1.3949	UU	450	2.9422	PL	450	58.3772
PW	450	1.1042	UU	450	2.9728	PL	450	56.3422
PW	475	1.1270	UU	475	2.3100	PL	475	58.9513
PW	475	0.7002	UU	475	2.6280	PL	475	59.7658
PW	475	0.7742	UU	475	4.1605	PL	475	57.2993
PW	500	0.3264	UU	500	3.0893	PL	500	54.4145
PW	500	0.7713	UU	500	2.9201	PL	500	59.5945
PW	500	0.4356	UU	500	4.6089	PL	500	60.2422
PW	425	0.5544	UU	425	2.0945	PL	425	54.3962
PW	425	0.7496	UU	425	2.1644	PL	425	43.2590
PW	425	0.8939	UU	425	1.6609	PL	425	47.2680
PW	450	0.8360	UU	450	1.9069	PL	450	55.9392
PW	450	1.3662	UU	450	3.0040	PL	450	57.1482
PW	450	1.1180	UU	450	3.0350	PL	450	56.4383
PW	475	1.1175	UU	475	2.3631	PL	475	55.5010
PW	475	0.7150	UU	475	2.6113	PL	475	56.5730
PW	475	0.8934	UU	475	3.7303	PL	475	56.2520
PW	500	0.2786	UU	500	2.9536	PL	500	56.0994
PW	500	0.8088	UU	500	2.6173	PL	500	59.7581
PW	500	0.4523	UU	500	4.1155	PL	500	61.5214
PW	425	0.5032	UU	425	2.1135	PL	425	53.9965
PW	425	0.7319	UU	425	2.4961	PL	425	43.2514
PW	425	0.7658	UU	425	1.8399	PL	425	47.2643
PW	450	0.9256	UU	450	2.5081	PL	450	55.9285
PW	450	1.4150	UU	450	3.1005	PL	450	57.1429
PW	450	1.1174	UU	450	3.0521	PL	450	56.4358
PW	475	1.1074	UU	475	2.2432	PL	475	58.3914
PW	475	0.7210	UU	475	2.6609	PL	475	57.8768
PW	475	0.8062	UU	475	3.9883	PL	475	56.4370
PW	500	0.2911	UU	500	2.9500	PL	500	56.2259
PW	500	0.7807	UU	500	3.2177	PL	500	59.6921
PW	500	0.4150	UU	500	4.4355	PL	500	61.3419

Minitab result for ash content in biochar:

Two-way ANOVA: Ash.char versus Biomass Type, Temp

Source	DF	SS	MS	F	P
Biomass Type	2	68298.1	34149.0	11327.67	0.000
Temp	3	277.7	92.6	30.71	0.000
Interaction	6	403.2	67.2	22.29	0.000
Error	96	289.4	3.0		
Total	107	69268.5			

S = 1.736   R-Sq = 99.58%   R-Sq(adj) = 99.53%

```
                  Individual 95% CIs For Mean Based on
Biomass           Pooled StDev
Type        Mean  +---------+---------+---------+---------
PL       55.1175                                    (*
PW        0.8046  (*
UU        2.7950   (*
                  +---------+---------+---------+---------
                  0        15        30        45
```

```
               Individual 95% CIs For Mean Based on
               Pooled StDev
Temp     Mean  --+---------+---------+---------+-------
425   16.8374   (---*----)
450   20.1165                      (---*----)
475   20.4335                        (---*----)
500   20.9021                           (---*----)
               --+---------+---------+---------+-------
               16.5      18.0      19.5      21.0
```

General Linear Model: Ash.char versus Biomass Type, Temp

Factor	Type	Levels	Values
Biomass Type	fixed	3	PL, PW, UU
Temp	fixed	4	425, 450, 475, 500

Analysis of Variance for Ash.char, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Biomass Type	2	68298.1	68298.1	34149.0	11327.67	0.000
Temp	3	277.7	277.7	92.6	30.71	0.000
Biomass Type*Temp	6	403.2	403.2	67.2	22.29	0.000
Error	96	289.4	289.4	3.0		
Total	107	69268.5				

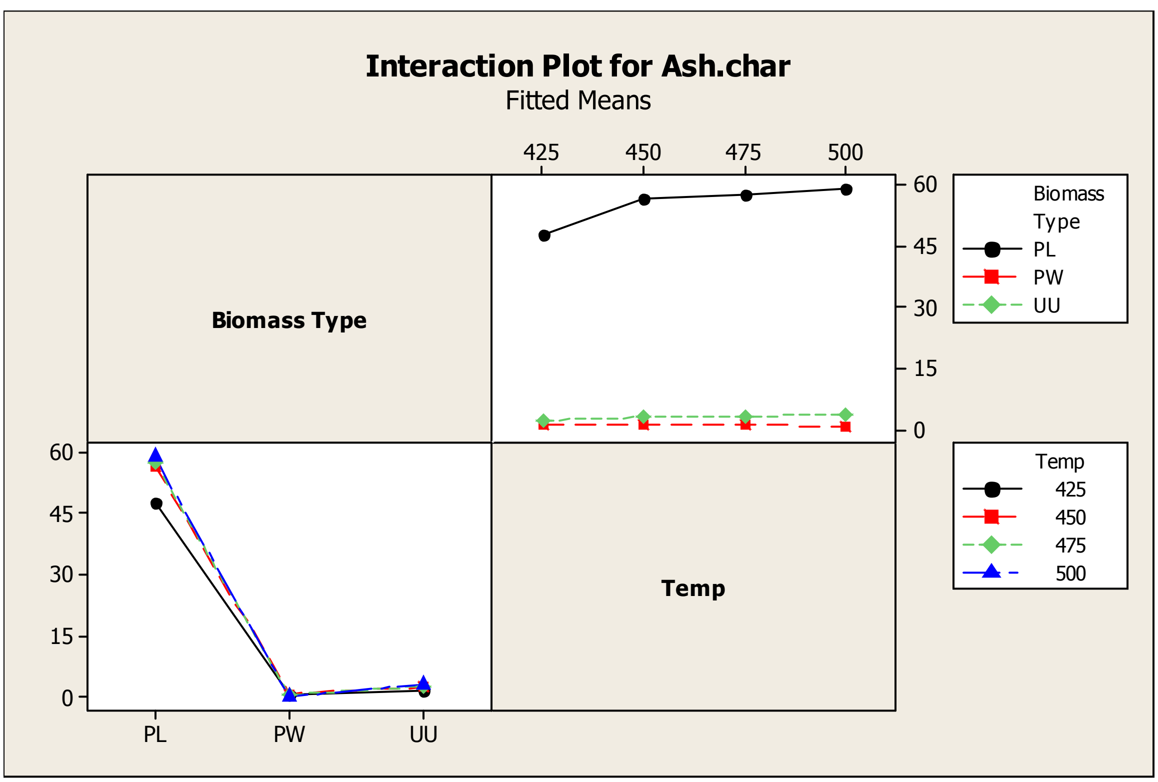
S = 1.73628   R-Sq = 99.58%   R-Sq(adj) = 99.53%

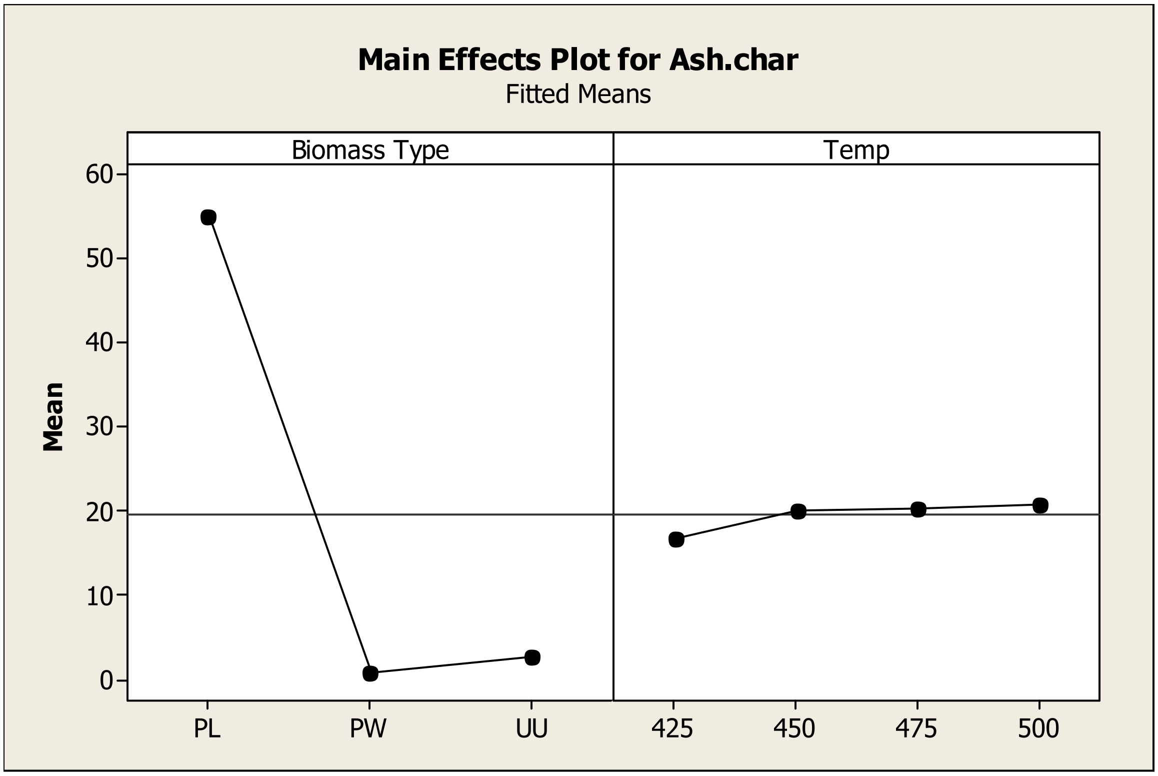
Unusual Observations for Ash.char

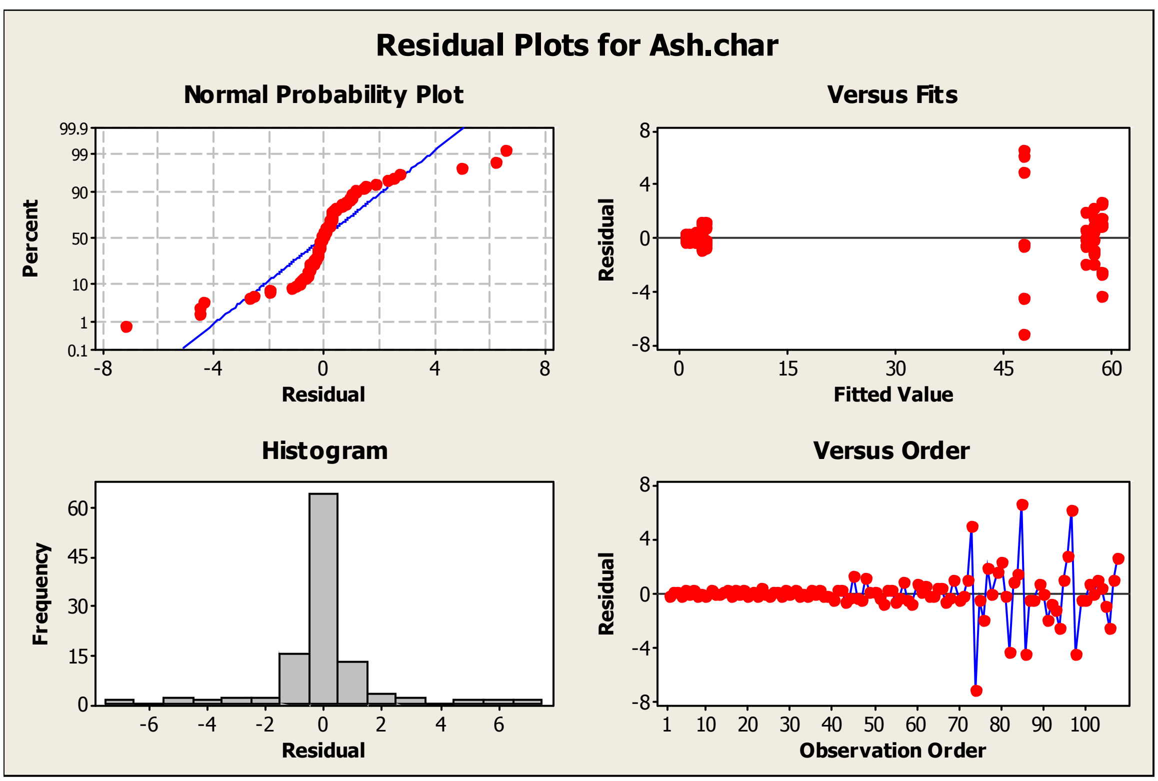
Obs	Ash.char	Fit	SE Fit	Residual	St Resid
73	52.7796	47.7798	0.5788	4.9998	3.05 R
74	40.5930	47.7798	0.5788	-7.1868	-4.39 R
82	54.4145	58.7655	0.5788	-4.3511	-2.66 R

```
 85   54.3962  47.7798  0.5788    6.6165      4.04 R
 86   43.2590  47.7798  0.5788   -4.5207     -2.76 R
 97   53.9965  47.7798  0.5788    6.2168      3.80 R
 98   43.2514  47.7798  0.5788   -4.5283     -2.77 R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Ash.char
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass
Type      Lower  Center   Upper  -----+---------+---------+---------+-
PW       -55.29  -54.31  -53.34  (*)
UU       -53.30  -52.32  -51.35    *)
                                 -----+---------+---------+---------+-
                                    -48       -32       -16         0

Biomass Type = PW  subtracted from:

Biomass
Type     Lower  Center  Upper  -----+---------+---------+---------+-
UU       1.015   1.990  2.966                                      *)
                               -----+---------+---------+---------+-
                                  -48       -32       -16         0
Tukey Simultaneous Tests
Response Variable Ash.char
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
PW           -54.31      0.4092   -132.7    0.0000
UU           -52.32      0.4092   -127.9    0.0000

Biomass Type = PW  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
UU            1.990      0.4092    4.864    0.0000


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Ash.char
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

Temp  Lower  Center  Upper  -----+---------+---------+---------+-
450   2.043   3.279  4.515              (-----*------)
475   2.360   3.596  4.832                (-----*-----)
500   2.828   4.065  5.301                  (-----*------)
                            -----+---------+---------+---------+-
                               0.0       2.0       4.0       6.0

Temp = 450  subtracted from:

Temp    Lower  Center  Upper  -----+---------+---------+---------+-
475   -0.9193  0.3171  1.553  (------*-----)
500   -0.4507  0.7857  2.022     (-----*-----)
                              -----+---------+---------+---------+-
                                 0.0       2.0       4.0       6.0
```

```
Temp = 475  subtracted from:

Temp    Lower  Center  Upper  -----+---------+---------+---------+-
500   -0.7677  0.4686  1.705   (-----*------)
                              -----+---------+---------+---------+-
                                  0.0       2.0       4.0       6.0


Tukey Simultaneous Tests
Response Variable Ash.char
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
450        3.279      0.4726    6.939     0.0000
475        3.596      0.4726    7.610     0.0000
500        4.065      0.4726    8.602     0.0000

Temp = 450  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
475       0.3171      0.4726   0.6710     0.9078
500       0.7857      0.4726   1.6626     0.3491


Temp = 475  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
500       0.4686      0.4726   0.9917     0.7545
```




Main Effects Plot for Ash.char
Fitted Means
Biomass Type
Temp
Mean
60
50
40
30
20
10
0
PL
PW
UU
425
450
475
500


Residual Plots for Ash.char
Normal Probability Plot
Percent
Residual
Versus Fits
Residual
Fitted Value
Histogram
Frequency
Residual
Versus Order
Residual
Observation Order

Minitab worksheet for heating value in biochar:

Biomass Type	Temp	HHV	Biomass Type	Temp	HHV	Biomass Type	Temp	HHV
PW	425	24978	UU	425	22714	PL	425	11810
PW	425	26727	UU	425	22581	PL	425	12352
PW	425	26138	UU	425	23599	PL	425	12118
PW	450	25655	UU	450	23784	PL	450	11194
PW	450	27444	UU	450	24736	PL	450	10668
PW	450	27208	UU	450	22079	PL	450	11407
PW	475	28302	UU	475	23066	PL	475	10978
PW	475	29061	UU	475	23684	PL	475	11445
PW	475	29497	UU	475	24203	PL	475	10646
PW	500	30234	UU	500	25037	PL	500	10824
PW	500	30239	UU	500	25820	PL	500	11074
PW	500	30901	UU	500	25957	PL	500	10446
PW	425	25067	UU	425	23409	PL	425	11891
PW	425	26644	UU	425	22286	PL	425	12615
PW	425	26286	UU	425	24075	PL	425	12117
PW	450	25692	UU	450	23540	PL	450	11120
PW	450	27561	UU	450	24642	PL	450	10771
PW	450	27175	UU	450	22820	PL	450	11668
PW	475	28248	UU	475	23490	PL	475	11068
PW	475	29319	UU	475	23733	PL	475	11448
PW	475	29736	UU	475	24573	PL	475	10624
PW	500	30191	UU	500	26437	PL	500	10829
PW	500	30248	UU	500	26418	PL	500	11239
PW	500	30862	UU	500	25463	PL	500	10483
PW	425	25004	UU	425	23012	PL	425	11789
PW	425	26675	UU	425	22379	PL	425	12490
PW	425	26228	UU	425	23702	PL	425	12209
PW	450	25711	UU	450	23581	PL	450	11202
PW	450	27602	UU	450	24698	PL	450	10758
PW	450	27222	UU	450	23002	PL	450	11661
PW	475	28397	UU	475	23545	PL	475	11081
PW	475	29168	UU	475	23789	PL	475	11493
PW	475	29641	UU	475	24612	PL	475	10651
PW	500	30124	UU	500	26359	PL	500	10841
PW	500	30272	UU	500	26138	PL	500	11112
PW	500	31007	UU	500	25879	PL	500	10477

Minitab result for heating value in biochar:

Two-way ANOVA: HHV.char versus Biomass Type, Temp

Source	DF	SS	MS	F	P
Biomass Type	2	5540540001	2770270001	8418.83	0.000
Temp	3	68237737	22745912	69.12	0.000
Interaction	6	96987365	16164561	49.12	0.000
Error	96	31589403	329056		
Total	107	5737354506			

S = 573.6   R-Sq = 99.45%   R-Sq(adj) = 99.39%

```
                  Individual 95% CIs For Mean Based on
Biomass           Pooled StDev
Type        Mean  --------+---------+---------+---------+-
PL       11294.4  (*
PW       28068.4                                  *)
UU       24134.5                          *)
                  --------+---------+---------+---------+-
                      15000     20000     25000     30000
```

```
               Individual 95% CIs For Mean Based on Pooled StDev
Temp     Mean    --+---------+---------+---------+-------
425   20403.5    (--*---)
450   20540.8      (--*---)
475   21314.7                 (--*---)
500   22404.1                                 (--*--)
                 --+---------+---------+---------+-------
               20300     21000     21700     22400
```

General Linear Model: HHV.char versus Biomass Type, Temp

Factor	Type	Levels	Values
Biomass Type	fixed	3	PL, PW, UU
Temp	fixed	4	425, 450, 475, 500

Analysis of Variance for HHV.char, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Biomass Type	2	5540540001	5540540001	2770270001	8418.83	0.000
Temp	3	68237737	68237737	22745912	69.12	0.000
Biomass Type*Temp	6	96987365	96987365	16164561	49.12	0.000
Error	96	31589403	31589403	329056		
Total	107	5737354506				

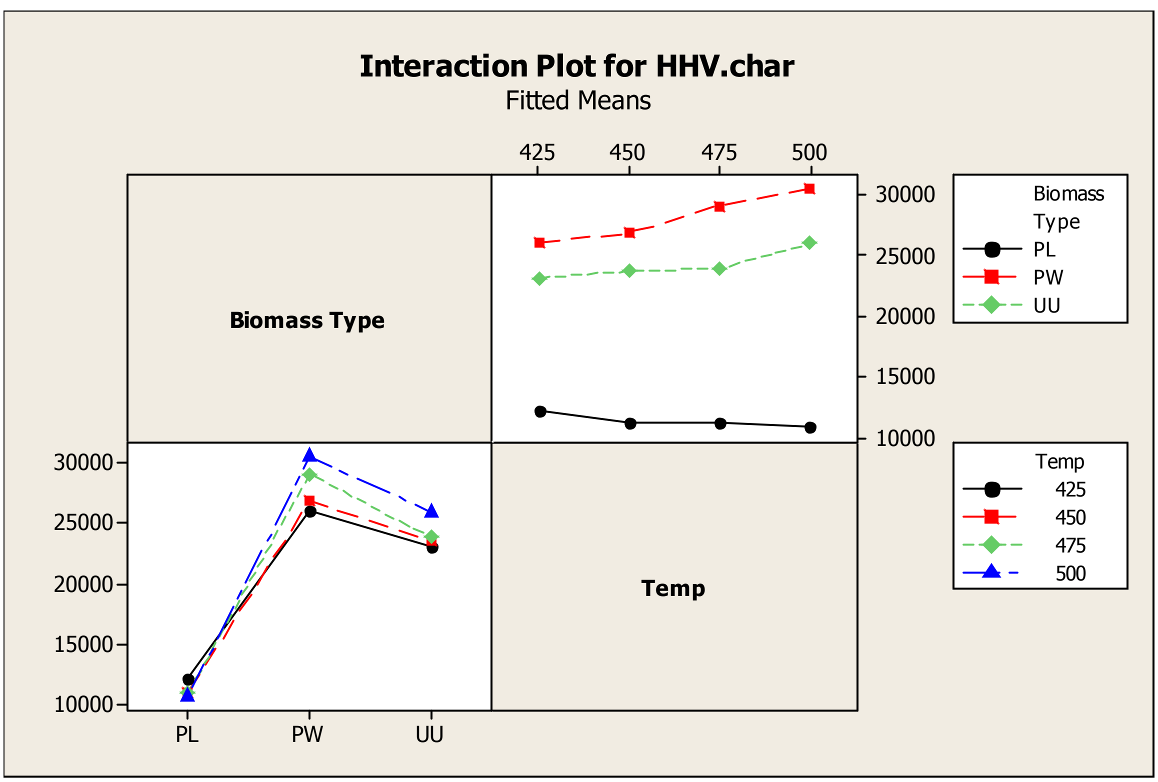
S = 573.634   R-Sq = 99.45%   R-Sq(adj) = 99.39%

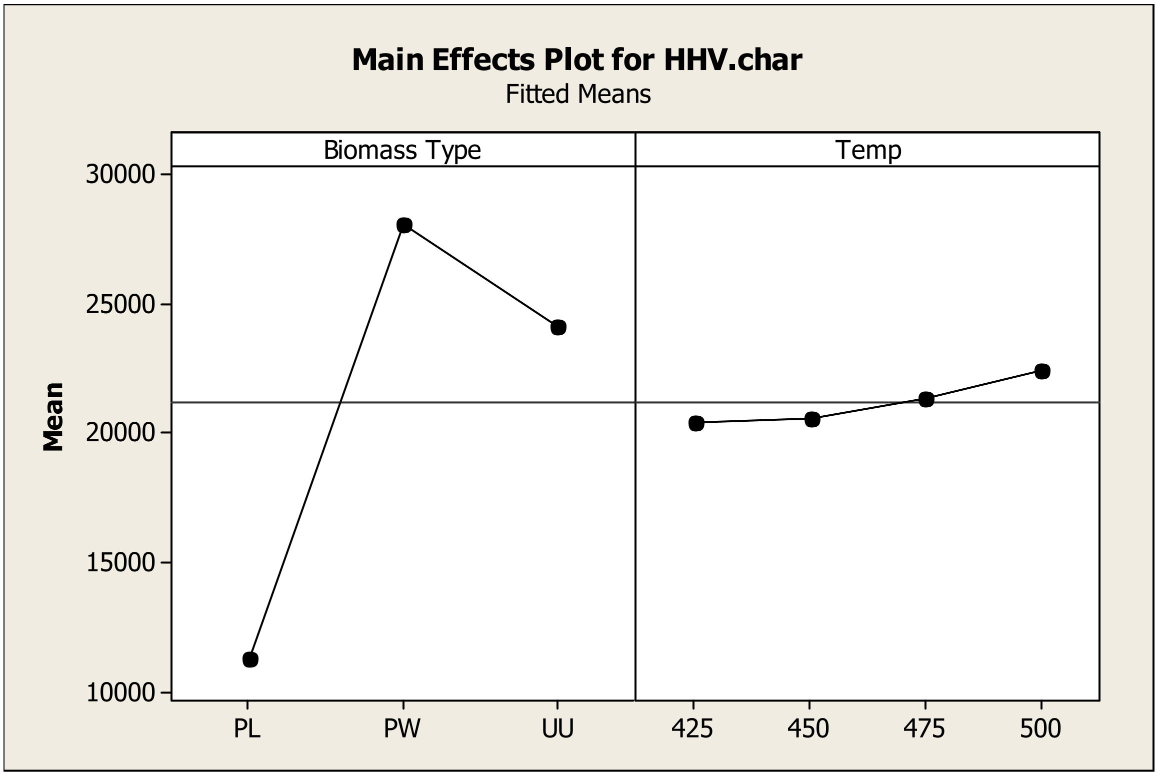
Unusual Observations for HHV.char

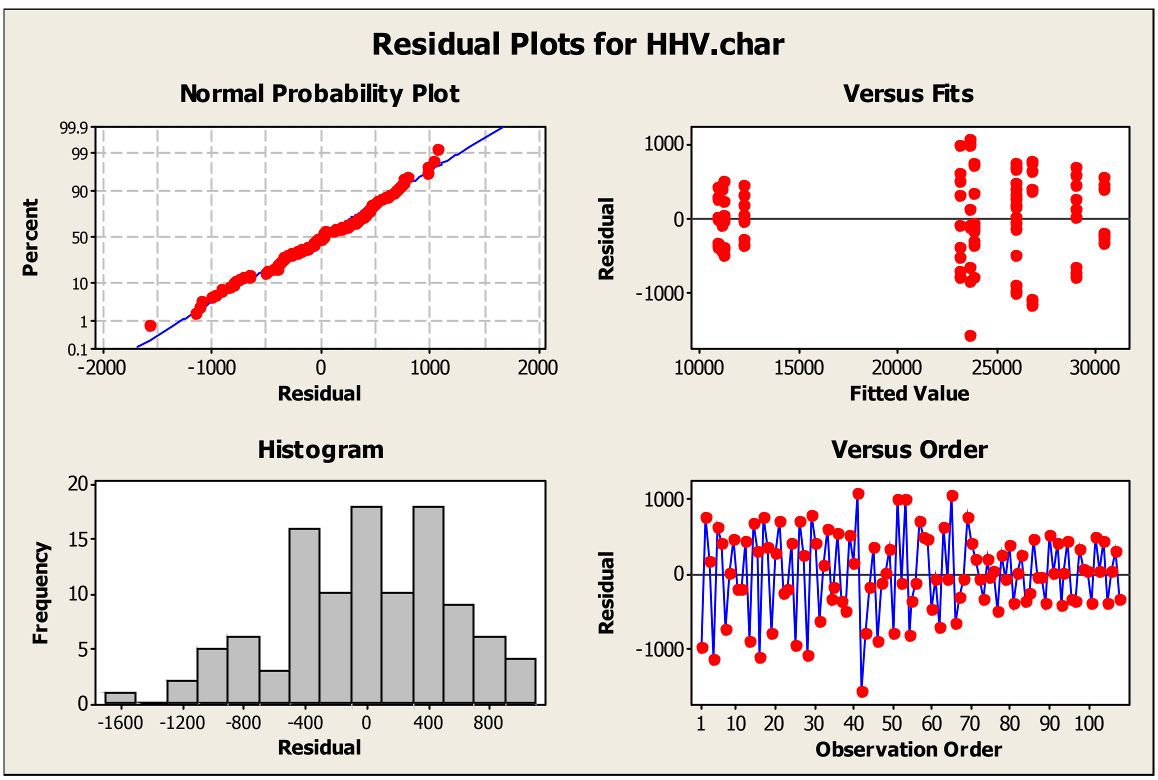
Obs	HHV.char	Fit	SE Fit	Residual	St Resid	
4	25655.0	26807.8	191.2	-1152.8	-2.13	R
16	25692.0	26807.8	191.2	-1115.8	-2.06	R
28	25711.0	26807.8	191.2	-1096.8	-2.03	R
41	24736.0	23653.6	191.2	1082.4	2.00	R

```
 42   22079.0  23653.6   191.2   -1574.6     -2.91 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable HHV.char
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass
Type     Lower  Center  Upper  -------+---------+---------+---------
PW       16452   16774  17096                                   (*
UU       12518   12840  13162                             *)
                               -------+---------+---------+---------
                                      0      6000     12000


Biomass Type = PW  subtracted from:

Biomass
Type     Lower  Center  Upper  -------+---------+---------+---------
UU       -4256   -3934  -3612  *)
                               -------+---------+---------+---------
                                      0      6000     12000


Tukey Simultaneous Tests
Response Variable HHV.char
All Pairwise Comparisons among Levels of Biomass Type
Biomass Type = PL  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
PW            16774       135.2   124.06    0.0000
UU            12840       135.2    94.97    0.0000


Biomass Type = PW  subtracted from:

Biomass  Difference       SE of           Adjusted
Type       of Means  Difference  T-Value   P-Value
UU            -3934       135.2   -29.10    0.0000


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable HHV.char
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

Temp   Lower  Center   Upper  ---+---------+---------+---------+---
450   -271.2   137.3   545.7  (----*----)
475    502.8   911.2  1319.7           (----*----)
500   1592.1  2000.6  2409.1                         (----*----)
                              ---+---------+---------+---------+---
                                 0       800      1600      2400


Temp = 450  subtracted from:

Temp   Lower  Center  Upper  ---+---------+---------+---------+---
475    365.5   774.0   1182         (----*----)
500   1454.9  1863.3   2272                     (----*----)
```

```
                                          ---+---------+---------+---------+---
                                             0       800      1600      2400


Temp = 475  subtracted from:

Temp  Lower  Center  Upper  ---+---------+---------+---------+---
500   680.9    1089   1498              (----*----)
                            ---+---------+---------+---------+---
                               0       800      1600      2400

Tukey Simultaneous Tests
Response Variable HHV.char
All Pairwise Comparisons among Levels of Temp
Temp = 425  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
450        137.3       156.1   0.8792     0.8156
475        911.2       156.1   5.8365     0.0000
500       2000.6       156.1  12.8142     0.0000

Temp = 450  subtracted from:

      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
475        774.0       156.1    4.957     0.0000
500       1863.3       156.1   11.935     0.0000

Temp = 475  subtracted from:
      Difference       SE of            Adjusted
Temp    of Means  Difference  T-Value    P-Value
500         1089       156.1    6.978     0.0000
```




Main Effects Plot for HHV.char
Fitted Means
Biomass Type
Temp
Mean
30000
25000
20000
15000
10000
PL
PW
UU
425
450
475
500


Residual Plots for HHV.char
Normal Probability Plot
Percent
Residual
Versus Fits
Residual
Fitted Value
Histogram
Frequency
Residual
Versus Order
Residual
Observation Order

APPENDIX C

SUPPLEMENTARY DATA FOR SELECTED FIGURES AND TABLES INVOLVED IN PRODUCTION OF BIO-OIL USING SACRIFICIAL BIO-BASED ADDITIVE

This appendix comprises of all the data, SAS code and SAS results involved in constructing the figures (Figure 28-29) and tables (Table14-16) of the second specific objective of this work. Data tables shown below represents the yield of bio-oil, char and gas and their physical properties, obtained while operating the respective biomass at selected temperatures.

C.1 EFFECT OF ADDITIVE ON PRODUCT YIELD

Table C.1.1. Data for yield of bio-oil obtained from different biomass mixture at 500°C (refer Figure 28).

Composition of poultry litter contained in the primary biomass (%)	Iteration No.	Product yield (wt. %)		
		Bio-oil	Bio-char	Gas
0	1	37.6	28.4	34
	2	36.4	23.6	40
	3	39.4	21	39.6
5	1	37	19.8	43.2
	2	37.4	19.6	43
	3	37.6	19.6	42.8
10	1	36	20.8	43.2
	2	36	21	43
	3	36.4	20.6	43
15	1	35.4	22.2	42.4
	2	35	22	43
	3	34.2	22.4	43.4
100	1	31.2	36	32.8
	2	29.4	38.4	32.2
	3	26	39.2	34.8

SAS code for bio-oil production (refer Table 14):

```
data OILYIELD;
input Comp yield;
datalines;
0       37.6
0       36.4
0       39.4
5       37
5       37.4
5       37.6
10      36
10      36
10      36.4
15      35.4
15      35
15      34.2
100     31.2
100     29.4
100     26
;
run;
proc anova data=OILYIELD;
class Comp;
model yield=Comp;
means Comp/ alpha=0.05;
run;
```

SAS result for bio-oil production (refer Table 14):

```
                              The ANOVA Procedure

                   Level of          ------------yield------------
                   Comp         N             Mean          Std Dev

                   0            3       37.8000000       1.50996689
                   5            3       37.3333333       0.30550505
                   10           3       36.1333333       0.23094011
                   15           3       34.8666667       0.61101009
                   100          3       28.8666667       2.64070698
Dependent Variable: yield

                                           Sum of
     Source                      DF       Squares     Mean Square    F Value    Pr > F

     Model                        4   156.6133333      39.1533333      20.03    <.0001

     Error                       10    19.5466667       1.9546667

     Corrected Total             14   176.1600000


                  R-Square     Coeff Var      Root MSE    yield Mean

                  0.889040      3.994554      1.398094      35.00000
```

```
Source                      DF        Anova SS     Mean Square    F Value    Pr > F

Comp                         4     156.6133333      39.1533333      20.03    <.0001
```

SAS code for bio-char production (refer Table 14):

```
data CHARYIELD;
input Comp yield;
datalines;
0      28.4
0      23.6
0      21
5      19.8
5      19.6
5      19.6
10     20.8
10     21
10     20.6
15     22.2
15     22
15     22.4
100    36
100    38.4
100    39.2
;
run;
proc anova data=CHARYIELD;
class Comp;
model yield=Comp;
means Comp/ alpha=0.05;
run;
```

SAS result for bio-char production (refer Table 14):

```
                                 The ANOVA Procedure

                     Level of          ------------yield-----------
                     Comp         N             Mean          Std Dev

                     0            3       24.3333333       3.75410886
                     5            3       19.6666667       0.11547005
                     10           3       20.8000000       0.20000000
                     15           3       22.2000000       0.20000000
                     100          3       37.8666667       1.66533280
Dependent Variable: yield
Source                     DF          Squares     Mean Square    F Value    Pr > F

      Model                      4     659.7493333     164.9373333      48.63    <.0001
      Error                     10      33.9200000       3.3920000
      Corrected Total           14     693.6693333
                  R-Square     Coeff Var      Root MSE     yield Mean
                  0.951101      7.374820      1.841738       24.97333
      Source                    DF        Anova SS     Mean Square    F Value    Pr > F
      Comp                      4     659.7493333     164.9373333      48.63    <.0001
```

SAS code for gas production (refer Table 14):

```
data GASYIELD;
input Comp yield;
datalines;
0      34
0      40
0      39.6
5      43.2
5      43
5      42.8
10     43.2
10     43
10     43
15     42.4
15     43
15     43.4
100    32.8
100    32.2
100    34.8
;
run;
proc anova data=GASYIELD;
class Comp;
model yield=Comp;
means Comp/ alpha=0.05;
run;
```

SAS result for gas production (refer Table 14):

```
                                The ANOVA Procedure

                        Level of          ------------yield------------
                        Comp          N           Mean          Std Dev

                        0             3     37.8666667       3.35459883
                        5             3     43.0000000       0.20000000
                        10            3     43.0666667       0.11547005
                        15            3     42.9333333       0.50332230
                        100           3     33.2666667       1.36137186

Dependent Variable: yield
                                          Sum of
  Source                      DF         Squares     Mean Square    F Value    Pr > F
      Model                        4     230.6826667      57.6706667      21.50    <.0001
      Error                       10      26.8266667       2.6826667
      Corrected Total             14     257.5093333

                       R-Square     Coeff Var      Root MSE    yield Mean

                       0.895823      4.091984      1.637885      40.02667


      Source                      DF        Anova SS     Mean Square    F Value    Pr > F

      Comp                         4     230.6826667      57.6706667      21.50    <.0001
```

C.2 EFFECT OF ADDITIVE ON PHYSICAL PROPERTIES OF BIO-OIL

Table C.2.1. Data for density of bio-oil (refer Table 15).

Comp. (%)	Iteration No.	Sample #1				Sample #2				Sample #3			
		Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)	Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)	Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)
0	1	5.7391	7.9807	2.2416	1120.8	5.818	8.0104	2.1924	1096.2	5.7492	8.0101	2.2609	1130.45
	2	5.7511	8.0867	2.3356	1167.8	5.7514	8.0567	2.3053	1152.65	5.8874	8.1847	2.2973	1148.65
	3	5.7589	8.0115	2.2526	1126.3	5.7563	8.01	2.2537	1126.85	5.7554	7.9898	2.2344	1117.2
5	1	5.7274	7.895	2.1676	1083.8	5.7484	8.0184	2.27	1135	5.7401	7.9606	2.2205	1110.25
	2	5.7254	7.96	2.2346	1117.3	5.7497	8.0153	2.2656	1132.8	5.7943	8.0244	2.2301	1115.05
	3	5.7353	8.0277	2.2924	1146.2	5.8543	8.1004	2.2461	1123.05	5.7368	8.0128	2.276	1138
10	1	5.7402	7.97	2.2298	1114.9	5.7373	7.9615	2.2242	1112.1	5.7327	7.9399	2.2072	1103.6
	2	5.7404	7.9982	2.2578	1128.9	5.7212	7.9422	2.221	1110.5	5.7452	7.9981	2.2529	1126.45
	3	5.7212	7.9422	2.221	1110.5	5.7431	7.9672	2.2241	1112.05	5.7601	8.0127	2.2526	1126.3
15	1	5.7408	7.9469	2.2061	1103.05	5.7432	7.9431	2.1999	1099.95	5.7675	7.9502	2.1827	1091.35
	2	5.7465	7.9497	2.2032	1101.6	5.7367	7.9401	2.2034	1101.7	5.8167	8.0013	2.1846	1092.3
	3	5.7376	7.9433	2.2057	1102.85	5.7416	7.9463	2.2047	1102.35	5.742	7.9834	2.2414	1120.7
100	1	5.7455	7.8697	2.1242	1062.1	5.7679	7.888	2.1201	1060.05	5.7398	7.871	2.1312	1065.6
	2	5.7554	7.8835	2.1281	1064.05	5.7775	7.9004	2.1229	1061.45	5.7501	7.8629	2.1128	1056.4
	3	5.7509	7.875	2.1241	1062.05	5.8174	7.9459	2.1285	1064.25	5.7596	7.8905	2.1309	1065.45

Note: Column "Comp (%)" represents the composition of poultry litter contained in the primary biomass (%).

SAS code for density of bio-oil:

```
data obj2;
input temp density;
datalines;
0       1120.8
0       1167.8
0       1126.3
0       1096.2
0       1152.65
0       1126.85
0       1130.45
0       1148.65
0       1117.2
5       1083.8
5       1117.3
5       1146.2
10      1114.9
10      1128.9
10      1110.5
15      1103.05
15      1101.6
15      1102.85
5       1135
5       1132.8
5       1123.05
10      1112.1
10      1110.5
10      1112.05
15      1099.95
15      1101.7
15      1102.35
5       1110.25
5       1115.05
5       1138
10      1103.6
10      1126.45
10      1126.3
15      1091.35
15      1092.3
15      1120.7
100     1062.1
100     1064.05
100     1062.05
100     1060.05
100     1061.45
100     1064.25
100     1065.6
100     1056.4
100     1065.45
;
run;
proc anova data=obj2;
class temp;
model density=temp;
means temp/ alpha=0.05;
```

```
run;
```

SAS result for density of bio-oil:

```
                              The ANOVA Procedure

                    Level of          -----------density-----------
                    temp        N             Mean          Std Dev

                    0           9       1131.87778       21.4262851
                    5           9       1122.38333       18.6907564
                    10          9       1116.14444        8.8585920
                    15          9       1101.76111        8.3896431
                    100         9       1062.37778        2.9223397

Dependent Variable: Density
                                               Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F
      Model                        4      26619.46922      6654.86731      34.45    <.0001
      Error                       40       7726.64722       193.16618
      Corrected Total             44      34346.11644

                R-Square     Coeff Var      Root MSE    density Mean
                0.775036      1.255607      13.89842        1106.909
      Source                      DF         Anova SS     Mean Square    F Value    Pr > F
      temp                         4      26619.46922      6654.86731      34.45    <.0001
```

Table C.2.2. Data for acidity (pH) of bio-oil (refer Table 15).

Composition of poultry litter contained in the primary biomass (%)	Iteration No.	Sample # 1	Sample # 2	Sample # 3
0	1	3.68	3.69	3.7
	2	3.74	3.73	3.73
	3	3.76	3.76	3.76
5	1	3.73	3.73	3.71
	2	3.69	3.68	3.69
	3	3.68	3.69	3.69
10	1	3.82	3.82	3.83
	2	3.84	3.84	3.83
	3	3.85	3.85	3.86
15	1	3.9	3.91	3.92
	2	3.95	3.95	3.96
	3	3.98	3.98	3.98
100	1	9.36	9.36	9.36
	2	9.44	9.44	9.44
	3	9.48	9.49	9.49

SAS code for acidity of bio-oil:

```
data obj2;
input temp pH;
datalines;
0      3.68
0      3.74
0      3.76
0      3.69
0      3.73
0      3.76
0      3.7
0      3.73
0      3.76
5      3.73
5      3.69
5      3.68
10     3.82
10     3.84
10     3.85
15     3.9
15     3.95
15     3.98
5      3.73
5      3.68
5      3.69
10     3.82
10     3.84
10     3.85
15     3.91
15     3.95
15     3.98
5      3.71
5      3.69
5      3.69
10     3.83
10     3.83
10     3.86
15     3.92
15     3.96
15     3.98
100    9.36
100    9.44
100    9.48
100    9.36
100    9.44
100    9.49
100    9.36
100    9.44
100    9.49
;
run;
proc anova data=obj2;
class temp;
model pH=temp;
means temp/ alpha=0.05;
```

```
run;
```

SAS result for acidity of bio-oil:

```
                              The ANOVA Procedure

                       Level of         --------------pH-------------
                       temp        N            Mean          Std Dev

                       0           9      3.72777778       0.03113590
                       5           9      3.69888889       0.01964971
                       10          9      3.83777778       0.01394433
                       15          9      3.94777778       0.03113590
                       100         9      9.42888889       0.05555278


Dependent Variable: pH

                                                Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F
      Model                        4      228.2280133      57.0570033    50893.3    <.0001
      Error                       40        0.0448444       0.0011211
      Corrected Total             44      228.2728578

                      R-Square     Coeff Var      Root MSE       pH Mean

                      0.999804      0.679413      0.033483      4.928222

      Source                      DF         Anova SS     Mean Square    F Value    Pr > F

      temp                         4      228.2280133      57.0570033    50893.3    <.0001
```

Table C.2.3. Data for water content of bio-oil (refer Table 15).

Sample	Sample wt (g)		Difference (g)	KFR vol (ml)		Difference (ml)	Water (wt%)
	Initial	Final		Initial	final		
methanol	0.0	2.4	2.4				40ml
water			5 µl	2.4	3.8	1.4	3.57
water			5 µl	3.8	5.2	1.4	3.57
0-1a	138.2234	138.1800	0.0434	14.6	16.1	1.5	19.20
0-1b	138.1800	138.1381	0.0419	16.1	17.6	1.5	19.89
0-1c	138.1381	138.1030	0.0351	17.6	19.0	1.4	22.16
0.2a	168.7295	168.6684	0.0611	19.0	21.2	2.2	20.00
0-2b	168.6491	168.5373	0.1118	21.2	25.1	3.9	19.38
0-2c	168.5373	168.5015	0.0358	25.1	26.3	1.2	18.62
0-3a	165.3967	165.3506	0.0461	0.0	1.6	1.6	19.28
0-3b	165.3501	165.2971	0.0530	1.6	3.4	1.8	18.87
0-3c	165.2971	165.2369	0.0602	3.4	5.0	1.6	14.77
5-1-A	110.6825	110.5420	0.1405	0	7.8	7.8	19.83

Sample	Sample wt (g)		Difference (g)	KFR vol (ml)		Difference (ml)	Water (wt%)
	Initial	Final		Initial	final		Initial
5-1-B	110.5420	110.3785	0.1635	7.8	16.4	8.6	18.79
5-1-C	110.2397	110.1612	0.0785	16.4	20.7	4.3	19.56
5-2-A	62.8978	62.7898	0.1080	20.7	26.5	5.8	19.18
5-2-B	62.7882	62.7081	0.0801	0.0	4.2	4.2	18.73
5-2-C	62.7041	62.6282	0.0759	4.2	8.3	4.1	19.29
5-3-a	132.7878	132.7380	0.0498	8.3	11.2	2.9	20.80
5-3-b	132.7381	132.6565	0.0816	11.2	16.1	4.9	21.45
5-3-c	132.6547	132.5855	0.0692	16.1	20.1	4	20.64
10-3-a	107.9407	107.8982	0.0425	20.1	22.7	2.6	21.85
10-3-b	107.8965	107.6907	0.2058	0.0	13.1	13.1	22.73
10-3-c	107.6907	107.5480	0.1427	13.1	21.7	8.6	21.52
10-4-a	115.5591	115.4468	0.1123	21.7	28.1	6.4	20.35
10-4-b	115.4447	115.3805	0.0642	0.0	4.0	4	22.25
10-4-c	115.3805	115.3000	0.0805	4.0	9.0	5	22.18
10-5-a	124.3572	124.2491	0.1081	9.0	15.6	6.6	21.81
10-5-b	124.2480	124.1590	0.0890	15.6	20.9	5.3	21.27
10-5-c	124.1596	124.0963	0.0633	20.9	24.5	3.6	20.31
15-1-a	124.4925	124.2895	0.2030	0.0	13.3	13.3	23.40
15-1-b	124.2800	124.2387	0.0413	13.3	15.9	2.6	22.48
15-1-c	124.2275	124.1678	0.0597	15.9	19.7	3.8	22.73
15-2-a	111.1373	110.8891	0.2482	0.0	16.2	16.2	23.31
15-2-b	110.8800	110.7162	0.1638	16.2	26.7	10.5	22.89
15-2-c	110.7127	110.6097	0.1030	0.0	6.1	6.1	21.15
15-3a	123.3551	123.2886	0.0665	6.1	10.2	4.1	22.02
15-3b	123.2886	123.0935	0.1951	10.2	23.1	12.9	23.61
15-3c	123.0906	123.0303	0.0603	23.1	26.9	3.8	22.51
100-1a	160.4940	160.4598	0.0342	0.0	3.0	3	28.63
100-1b	160.4498	160.4243	0.0255	3.0	5.5	2.5	32.00
100-1c	160.4235	160.3956	0.0279	5.5	8.1	2.6	30.42
100.2a	93.9595	93.9126	0.0469	8.1	11.8	3.7	25.75
100-2b	93.9126	93.8715	0.0411	11.8	15.6	3.8	30.18
100-2c	93.8715	93.8273	0.0442	15.6	19.3	3.7	27.32
100-3a	116.8931	116.8465	0.0466	19.3	23.3	4	28.02
100-3b	116.8457	116.7943	0.0514	0.0	4.6	4.6	29.21
100-3c	116.7943	116.7545	0.0398	4.6	8.3	3.7	30.34

SAS code for water content of bio-oil:

```
data obj2;
input temp water;
datalines;
0       19.88863962
0       22.15892877
0       20.00365303
0       19.37986047
0       18.62198883
0       19.28177007
0       18.86793962
0       14.76560797
5       19.82715032
5       18.7854981
5       19.56324166
5       19.17989648
5       18.72659401
5       19.29230422
5       20.79747811
5       21.446081
5       20.64409827
10      21.84874212
10      22.73358596
10      21.52367863
10      20.35364702
10      22.25189408
10      22.18278882
10      21.80520944
10      21.26806034
10      20.31144455
15      23.39901759
15      22.4835724
15      22.7327139
15      23.31069694
15      22.89377564
15      21.15118146
15      22.01933669
15      23.61426658
15      22.50651774
100     31.99901961
100     30.4162724
100     25.7493177
100     30.17717762
100     27.32223982
100     28.01630901
100     29.21
100     30.34278894
;
run;
proc anova data=obj2;
class temp;
model water=temp;
means temp/ alpha=0.05;
run;
```

SAS result for water content of bio-oil:

```
                              The ANOVA Procedure

               Level of          ------------water------------
               temp         N            Mean          Std Dev

               0            8      19.1210485       2.06925471
               5            9      19.8069269       0.95505922
               10           9      21.5865612       0.82778045
               15           9      22.6790088       0.76473287
               100          8      29.1541406       2.01396068

Dependent Variable: water
                                        Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F
      Model                        4     518.1287322     129.5321830      64.92    <.0001
      Error                       38      75.8223682       1.9953255
      Corrected Total             42     593.9511004
                R-Square     Coeff Var      Root MSE    water Mean
                0.872342      6.308337      1.412560      22.39195
      Source                      DF        Anova SS     Mean Square    F Value    Pr > F
      temp                         4     518.1287322     129.5321830      64.92    <.0001
```

Table C.2.4. Data for higher heating value of bio-oil (refer Table 15).

Composition of poultry litter contained in the primary biomass (%)	Iteration No.	Weight of the sample #1	Energy required (J/g)	Weight of the sample #2	Energy required (J/g)	Weight of the sample #3	Energy required (J/g)
0	1	0.5683	21333	0.5462	21268	0.5183	21424
	2	0.654	22270	0.5483	22238	0.5032	22309
	3	0.5	22368	0.6093	22472	0.5333	22461
5	1	0.614	20831	0.5233	20708	0.5449	20928
	2	0.4722	21677	0.4991	21789	0.6038	21751
	3	0.5488	21076	0.537	21233	0.5139	21217
10	1	0.5667	19511	0.5137	19402	0.552	19567
	2	0.5485	20363	0.4992	20291	0.5048	20199
	3	0.4878	19780	0.5361	19501	0.5403	19543
15	1	0.49	18015	0.5079	17995	0.6372	17891
	2	0.5731	18363	0.5238	18674	0.4254	18549
	3	0.5538	17762	0.5187	17362	0.5506	17293
100	1	0.526	14324	0.5872	14561	0.5174	13673
	2	0.6564	13741	0.4398	13786	0.4561	13101
	3	0.5436	13790	0.558	14390	0.5926	13682

SAS code for higher heating value of bio-oil:

```
data OILHHV;
input temp hhv;
datalines;
0     21333
0     22270
0     22368
0     21268
0     22238
0     22472
0     21424
0     22309
0     22461
5     20831
5     21677
5     21076
10    19511
10    20363
10    19780
15    18015
15    18363
15    17762
5     20708
5     21789
5     21233
10    19402
10    20291
10    19501
15    17995
15    18674
15    17362
5     20928
5     21751
5     21217
10    19567
10    20199
10    19543
15    17891
15    18549
15    17293
100   14324
100   13741
100   13790
100   14561
100   13786
100   14390
100   13673
100   13101
100   13682
;
run;
proc anova data=OILHHV;
class temp;
model hhv=temp;
means temp/ alpha=0.05;
```

```
run;
```

SAS result for higher heating value of bio-oil:

```
                              The ANOVA Procedure
                 Level of          -------------hhv-------------
                 temp         N             Mean          Std Dev

                 0            9       22015.8889       513.075395
                 5            9       21245.5556       407.482549
                 10           9       19795.2222       382.280910
                 15           9       17989.3333       482.453366
                 100          9       13894.2222       453.366237
Dependent Variable: hhv
                                          Sum of
      Source                    DF       Squares     Mean Square    F Value    Pr > F
      Model                      4   376741647.7      94185411.9     464.55    <.0001
      Error                     40     8109834.2        202745.9
      Corrected Total           44   384851481.9
                 R-Square     Coeff Var      Root MSE      hhv Mean
                 0.978927      2.371351      450.2731      18988.04
      Source                    DF       Anova SS    Mean Square    F Value    Pr > F
      temp                       4   376741647.7      94185411.9     464.55    <.0001
```

Table C.2.5. Data for ash content of bio-oil (refer Table 15).

Comp (%)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
0	1	14.2752	14.2747	16.927	2.6523	14.2799	0.0052	0.1961
	2	14.4982	14.4972	17.8152	3.318	14.5091	0.0119	0.3586
	3	14.8937	14.8931	17.4977	2.6046	14.9042	0.0111	0.4262
5	1	15.495	15.4945	17.5337	2.0392	15.5013	0.0068	0.3335
	2	14.4316	14.4295	16.5318	2.1023	14.4386	0.0091	0.4329
	3	14.7363	14.735	17.4849	2.7499	14.7469	0.0119	0.4327
10	1	14.9405	14.9377	17.597	2.6593	14.946	0.0083	0.3121
	2	14.9751	14.9744	17.4221	2.4477	14.9811	0.0067	0.2737
	3	14.3648	14.3642	17.554	3.1898	14.3753	0.0111	0.3480
15	1	15.1814	15.1813	18.0003	2.819	15.1925	0.0112	0.3973
	2	14.1313	14.1302	16.5617	2.4315	14.1416	0.0114	0.4688
	3	14.2161	14.2161	15.3151	1.099	14.2195	0.0034	0.3094
100	1	9.7761	9.7752	10.6453	0.8701	9.7764	0.0012	0.1379
	2	9.4736	9.4728	10.2990	0.8262	9.4741	0.0013	0.1573
	3	12.1083	12.1074	12.9368	0.8294	12.1085	0.0011	0.1326

Comp (%)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
0	1	14.5044	14.5033	17.2331	2.7298	14.5084	0.0051	0.1868
	2	16.6669	16.666	17.9489	1.2829	16.6708	0.0048	0.3742
	3	15.4693	15.4689	18.1079	2.639	15.4805	0.0116	0.4396
5	1	14.7438	14.7436	16.9911	2.2475	14.7522	0.0086	0.3826
	2	13.7298	13.7286	16.5476	2.819	13.7401	0.0115	0.4079
	3	15.3537	15.3532	18.146	2.7928	15.3658	0.0126	0.4512
10	1	12.9886	12.9883	15.4419	2.4536	12.9957	0.0074	0.3016
	2	12.8977	12.8958	15.0839	2.1881	12.9012	0.0054	0.2468
	3	15.1206	15.1205	17.4393	2.3188	15.1289	0.0084	0.3623
15	1	14.3467	14.3466	17.4444	3.0978	14.3574	0.0108	0.3486
	2	15.0049	15.0045	17.1571	2.1526	15.0146	0.0101	0.4692
	3	15.1392	15.1383	17.1398	2.0015	15.1434	0.0051	0.2548
100	1	9.6727	9.6724	10.2071	0.5347	9.6731	0.0007	0.1309
	2	12.4191	12.4189	13.7764	1.3575	12.4211	0.0022	0.1621
	3	13.0795	13.0790	15.2365	2.1575	13.0821	0.0031	0.1437

Comp (%)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
0	1	14.2755	14.2745	15.5529	1.2784	14.2772	0.0027	0.2112
	2	14.4982	14.4975	15.8659	1.3684	14.5021	0.0046	0.3362
	3	14.8938	14.893	16.2628	1.3698	14.8992	0.0062	0.4526
5	1	15.4954	15.4948	17.2838	1.789	15.5012	0.0064	0.3577
	2	14.4306	14.4296	15.6692	1.2396	14.4344	0.0048	0.3872
	3	14.7355	14.7355	15.7226	0.9871	14.7395	0.004	0.4052
10	1	14.9388	14.9385	16.2051	1.2666	14.9427	0.0042	0.3316
	2	14.9747	14.9744	16.9581	1.9837	14.9797	0.0053	0.2672
	3	14.3644	14.3642	17.2016	2.8374	14.3743	0.0101	0.3560

Comp (%)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
15	1	15.1818	15.1815	16.42	1.2385	15.1858	0.0043	0.3472
	2	14.1304	14.1303	16.2041	2.0738	14.1392	0.0089	0.4292
	3	14.2162	14.2161	15.7834	1.5673	14.221	0.0049	0.3126
100	1	9.7761	9.7752	10.2945	0.5193	9.7759	0.0007	0.1348
	2	9.4736	9.4728	10.7893	1.3165	9.4751	0.0023	0.1747
	3	12.1083	12.1074	13.0002	0.8928	12.1087	0.0013	0.1456

SAS code for ash content of bio-oil:

```
data obj2;
input temp ash;
datalines;
0       0.196056253
0       0.358649789
0       0.426169085
0       0.186826874
0       0.374152311
0       0.43956044
0       0.211201502
0       0.336159018
0       0.452620821
5       0.333464104
5       0.432859249
5       0.432743009
10      0.31211221
10      0.273726355
10      0.3479842
15      0.397304009
15      0.468846391
15      0.309372157
5       0.382647386
5       0.40794608
5       0.451160126
10      0.301597652
10      0.246789452
10      0.362256339
15      0.348634515
15      0.469200037
15      0.254808893
5       0.357741755
5       0.387221684
5       0.405227434
10      0.3315964
10      0.267177497
10      0.355959681
```

```
15    0.347194187
15    0.429163854
15    0.312639571
100   0.137915182
100   0.157346889
100   0.132625995
100   0.130914532
100   0.162062615
100   0.14368482
100   0.134796842
100   0.174705659
100   0.145609319
;
run;
proc anova data=obj2;
class temp;
model ash=temp;
means temp/ alpha=0.05;
run;
```

SAS result for ash content of bio-oil:

The ANOVA Procedure

Level of temp	N	ash Mean	ash Std Dev
0	9	0.33126623	0.10702461
5	9	0.39900120	0.03796028
10	9	0.31102220	0.04177768
15	9	0.37079596	0.07505245
100	9	0.14662909	0.01504176

Dependent Variable: HHV

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.34870971	0.08717743	21.26	<.0001
Error	40	0.16399800	0.00409995		
Corrected Total	44	0.51270771			

R-Square	Coeff Var	Root MSE	ash Mean
0.680134	20.53963	0.064031	0.311743

Source	DF	Anova SS	Mean Square	F Value	Pr > F
temp	4	0.34870971	0.08717743	21.26	<.0001

Table C.2.6. Data for solid content of bio-oil (refer Table 15).

Comp. (%)	Iteration No.	Sample #1			
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
0	1	320.5	312.4	314.7	0.23
	2	321.7	313.4	320.1	0.67
	3	324.7	316.4	324.6	0.82
5	1	547.8	530.4	536.2	0.58
	2	550.4	534.6	539.9	0.53
	3	548	531.1	537.2	0.61
10	1	550.2	535	541.7	0.67
	2	549	534.6	541.9	0.73
	3	543.8	525.8	532.2	0.64
15	1	549.5	535.5	543.8	0.83
	2	549.5	531.4	539.7	0.83
	3	562.4	542.4	551.6	0.92
100	1	320.4	312.9	313.9	0.10
	2	330.8	322.6	324.1	0.14
	3	320.9	312.5	314.6	0.21

Comp. (%)	Iteration No.	Sample #2			
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
0	1	322.6	314.4	317.1	0.27
	2	323.9	315.6	323.3	0.75
	3	330	320.5	329	0.85
5	1	544.5	525.6	531.7	0.61
	2	550.8	534.7	540.8	0.61
	3	548.4	530.2	537.1	0.69
10	1	550.8	535.1	541.1	0.6
	2	557.3	540.6	547.9	0.73
	3	557.5	546	552.1	0.61
15	1	557.3	540	548	0.8
	2	553.8	536.1	544.5	0.84
	3	545.1	527.9	537.5	0.96
100	1	317.7	310.4	311.8	0.14
	2	317.9	311.2	312.8	0.16
	3	325.4	317.7	320.1	0.24

Comp. (%)	Iteration No.	Sample #3			
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
0	1	330.2	321.7	324.6	0.29
	2	330.9	322.4	329.4	0.71
	3	339.1	331.5	339.3	0.76
5	1	543.6	526.7	532.2	0.55
	2	549.3	534.1	539.5	0.54
	3	521.7	520.1	526.8	0.67
10	1	534.6	523.5	529.4	0.59
	2	538.9	526.3	534.1	0.78
	3	550.4	533.8	539	0.52
15	1	554.3	538.4	546.4	0.8
	2	548.1	524.9	533.2	0.83
	3	539.5	522.1	531.7	0.96
100	1	329.7	321.6	323.1	0.15
	2	334.8	328.9	330.7	0.18
	3	329.1	320.5	323.1	0.26

Note: Here, weight of the bio-oil was assumed as one gram (1g).

SAS code for solid content of bio-oil:

```
data obj2;
input temp solid;
datalines;
0      0.226266601
0      0.665210485
0      0.817628876
0      0.26973027
0      0.748590317
0      0.847964884
0      0.290174104
0      0.713412148
0      0.759567631
5      0.58
5      0.53
5      0.61
10     0.67
10     0.73
10     0.64
15     0.83
15     0.83
15     0.92
5      0.61
5      0.61
5      0.69
```

```
10      0.6
10      0.73
10      0.61
15      0.8
15      0.84
15      0.96
5       0.55
5       0.54
5       0.67
10      0.59
10      0.78
10      0.52
15      0.8
15      0.83
15      0.96
100     0.099245732
100     0.142126208
100     0.208498809
100     0.139109698
100     0.156571093
100     0.235594385
100     0.148558978
100     0.176956351
100     0.257834193
;
run;
proc anova data=obj2;
class temp;
model solid=temp;
means temp/ alpha=0.05;
run;
```

SAS result for solid content of bio-oil:

The ANOVA Procedure

Level of temp	N	solid Mean	solid Std Dev
0	9	0.59317170	0.25441888
5	9	0.59888889	0.05555278
10	9	0.65222222	0.08273116
15	9	0.86333333	0.06500000
100	9	0.17383283	0.05098184

Dependent Variable: Solid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	2.25834349	0.56458587	34.64	<.0001
Error	40	0.65186937	0.01629673		
Corrected Total	44	2.91021287			

```
                    R-Square     Coeff Var      Root MSE    solid Mean

                    0.776006      22.15182      0.127659      0.576290


Source                    DF        Anova SS     Mean Square    F Value    Pr > F

temp                       4      2.25834349      0.56458587      34.64    <.0001
```

Table C.2.7. Data for TAN No. of bio-oil (refer Table 15).

Sample Name	Wt. of the sample	Amt. of KOH in ml	TAN No.
P.W, 1-stage-a	1.0086	10	55.64
P.W, 1-stage-b	1.0087	10	55.64
P.W, 1-stage-c	1.0054	10	55.82
5% P.L -a	1.0063	7.5	41.83
5% P.L -b	1.0043	7.25	40.51
5% P.L -c	1.009	7.5	41.71
10% P.L-a	1.0013	5.25	29.42
10% P.L-b	1.0051	5.25	29.31
10% P.L-c	1.0075	5	27.85
15% P.L-a	1.0053	5	27.91
15% P.L-b	1.0047	5	27.93
15% P.L-c	1.007	4.5	25.08
P.L, 1-stage-a	1	0	0.00
P.L, 1-stage-b	1	0	0.00
P.L, 1-stage-c	1	0	0.00

SAS code for TAN No. of bio-oil:

```
data obj2;
input temp TAN;
datalines;
0      55.64
0      55.64
0      55.82
5      41.82649309
5      40.51279498
5      41.71456888
10     29.42474783
10     29.31350114
10     27.85111663
15     27.91206605
15     27.92873495
15     25.07845084
100    0.00
100    0.00
100    0.00
;
```

```
run;
proc anova data=obj2;
class temp;
model TAN=temp;
means temp/ alpha=0.05;
run;
```

SAS result for TAN No. of bio-oil:

```
                              The ANOVA Procedure

                        Level of          -------------TAN-------------
                        temp         N            Mean          Std Dev

                        0            3      55.7000000       0.10392305
                        5            3      41.3512857       0.72830743
                        10           3      28.8631219       0.87818558
                        15           3      26.9730839       1.64082157
                        100          3       0.0000000       0.00000000

Dependent Variable: TAN

                                            Sum of
      Source                      DF       Squares     Mean Square    F Value    Pr > F

      Model                        4   5094.386632     1273.596658    1590.11    <.0001

      Error                       10      8.009474        0.800947

      Corrected Total             14   5102.396106


                       R-Square     Coeff Var      Root MSE      TAN Mean

                       0.998430      2.926847      0.894957      30.57750


      Source                      DF       Anova SS    Mean Square    F Value    Pr > F

      temp                         4   5094.386632     1273.596658    1590.11    <.0001
```

C.3 VISCOSITY ANALYSIS OF DIFFERENT BIO-OILS

Table C.3.1. Data for Figure 29

5 % of P.L			
Shear Stress (Pa)	Shear Rate (1/s)	Viscosity (Pas)	Log (Viscosity)
0.022	0.030	0.61	-0.73095
0.303	2.065	0.35	-0.80173
0.618	4.855	0.22	-0.86832
0.939	7.723	0.14	-0.92053
1.234	11.008	0.10	-0.94188
1.553	11.921	0.11	-0.93919
1.837	16.926	0.09	-0.95877
2.162	20.281	0.08	-0.95218
2.431	22.825	0.08	-0.96214
2.730	24.553	0.07	-0.97212
3.002	29.992	0.05	-0.97724
3.255	24.439	0.06	-0.98055
3.528	32.195	0.07	-0.99025
3.764	38.078	0.06	-0.99225
4.013	39.321	0.06	-0.99978
4.250	41.203	0.06	-1.00854
4.488	45.075	0.06	-1.00923
4.692	48.531	0.06	-1.01476
4.944	50.065	0.07	-1.02124
5.187	53.221	0.07	-1.02325
5.452	56.002	0.07	-1.02521
5.663	59.397	0.07	-1.02684
5.945	63.188	0.07	-1.02899
6.202	68.840	0.06	-1.03082
6.455	73.673	0.05	-1.03291
6.699	72.338	0.06	-1.03317
6.976	77.182	0.05	-1.03423
7.204	81.250	0.05	-1.036
7.507	80.174	0.05	-1.03132
7.780	85.516	0.05	-1.03417
8.033	88.638	0.05	-1.03586
8.256	86.986	0.04	-1.03767
8.528	95.563	0.04	-1.03717
8.782	86.446	0.05	-1.03861
9.025	96.415	0.05	-1.0401

10 % of P.L			
Shear Stress (Pa)	Shear Rate (1/s)	Viscosity (Pas)	Log(Viscosity)
0.009	0.030	1.17	-0.36653
0.867	1.953	0.89	-0.36333
1.687	4.832	0.66	-0.4593
2.320	7.729	0.51	-0.52307
3.097	10.694	0.42	-0.5369
3.884	13.592	0.40	-0.54714
4.581	16.728	0.38	-0.55952
5.273	19.460	0.35	-0.56951
6.097	22.479	0.33	-0.56373
6.973	25.751	0.30	-0.55799
7.534	28.467	0.29	-0.57889
8.168	31.135	0.27	-0.58603
8.661	34.947	0.24	-0.59469
9.369	37.636	0.20	-0.60305
9.429	40.156	0.21	-0.63449
9.694	43.948	0.19	-0.64832
10.485	44.198	0.18	-0.63944
10.762	49.120	0.13	-0.66452
10.948	46.458	0.16	-0.67516
10.802	52.051	0.11	-0.70737
10.462	63.192	0.08	-0.74242
10.819	54.030	0.09	-0.74456
10.725	68.320	0.07	-0.77801
10.817	64.504	0.06	-0.79263
10.893	70.001	0.06	-0.80532
11.126	73.085	0.04	-0.82246
11.564	76.728	0.04	-0.80033
11.866	79.146	0.02	-0.82206
11.867	77.575	0.02	-0.84394
11.944	85.508	0.01	-0.85658
11.835	81.284	0.01	-0.86748
12.217	89.739	0.01	-0.87092
11.976	93.563	0.01	-0.89083
11.371	95.715	0.01	-0.90354
10.495	98.691	0.01	-0.98611

15 % of P.L			
Shear Stress (Pa)	Shear Rate (1/s)	Viscosity (Pas)	Log(Viscosity)
0.009	0.029	0.51	-0.13734
1.031	2.034	0.32	-0.26727
1.917	4.868	0.27	-0.41504
2.397	7.876	0.25	-0.50403
3.316	10.927	0.24	-0.51196
3.805	13.733	0.22	-0.55944
4.298	16.529	0.20	-0.58853
5.032	18.415	0.22	-0.5858
5.378	21.798	0.22	-0.6263
5.808	26.022	0.20	-0.64214
6.132	28.416	0.20	-0.66583
6.769	28.831	0.20	-0.65691
7.488	33.101	0.21	-0.65637
8.298	37.037	0.21	-0.64338
8.900	40.465	0.20	-0.66138
9.384	43.591	0.19	-0.66462
10.015	46.035	0.19	-0.65785
10.614	49.401	0.18	-0.66637
10.978	51.313	0.18	-0.68485
11.299	54.325	0.16	-0.68674
11.661	57.514	0.15	-0.69379
12.011	60.787	0.15	-0.6981
12.258	63.783	0.14	-0.71366
12.465	67.418	0.12	-0.72832
12.433	70.218	0.12	-0.7478
12.472	72.538	0.10	-0.77009
12.531	75.162	0.10	-0.78278
12.333	78.001	0.09	-0.80646
11.535	81.459	0.08	-0.84451
11.737	80.007	0.07	-0.85996
11.664	85.634	0.04	-0.87005
10.401	84.825	0.06	-0.94435
10.445	94.970	0.04	-0.94831
10.951	89.528	0.05	-0.93565
10.536	99.349	0.04	-0.98481

C.4 EFFECT OF ADDITIVE ON PHYSICAL PROPERTIES OF BIO-CHAR

Table C.4.1. Data for higher heating value of bio-char (refer Table 16).

Comp. (%)	Iteration No.	Weight of the sample #1	Energy required (J/g)	Weight of the sample #2	Energy required (J/g)	Weight of the sample #3	Energy required (J/g)
0	1	0.4819	30234	0.4862	30191	0.6028	30124
	2	0.6459	30239	0.5521	30248	0.5696	30272
	3	0.513	30901	0.5189	30862	0.6452	31007
5	1	0.48	28590	0.5247	28496	0.6072	28505
	2	0.4362	29061	0.4508	29100	0.5046	29089
	3	0.4558	29126	0.6106	29108	0.5576	29148
10	1	0.4871	27384	0.5629	27368	0.4777	27402
	2	0.5433	27299	0.4994	27345	0.509	27318
	3	0.4652	26977	0.6173	27008	0.5133	27019
15	1	0.5157	26291	0.4877	26273	0.5523	26314
	2	0.558	25830	0.5016	25774	0.5247	25783
	3	0.5792	25685	0.4995	25631	0.6629	25690
100	1	0.5262	10824	0.5415	10829	0.4987	10841
	2	0.5036	11074	0.5315	11239	0.5678	11112
	3	0.5752	10446	0.5763	10483	0.5129	10477

SAS code for higher heating value of bio-char:

```
data obj2;
input temp HHV;
datalines;
0      30234
0      30239
0      30901
0      30191
0      30248
0      30862
0      30124
0      30272
0      31007
5      28590
5      29061
5      29126
10     27384
10     27299
10     26977
15     26291
15     25830
15     25685
5      28496
```

```
5       29100
5       29108
10      27368
10      27345
10      27008
15      26273
15      25774
15      25631
5       28505
5       29089
5       29148
10      27402
10      27318
10      27019
15      26314
15      25783
15      25690
100     10824
100     11074
100     10446
100     10829
100     11239
100     10483
100     10841
100     11112
100     10477
;
run;
proc anova data=obj2;
class temp;
model HHV=temp;
means temp/ alpha=0.05;
run;
```

SAS result for higher heating value of bio-char:

The ANOVA Procedure

Level of temp	N	HHV Mean	HHV Std Dev
0	9	30453.1111	357.128984
5	9	28913.6667	289.643315
10	9	27235.5556	178.749204
15	9	25919.0000	286.641762
100	9	10813.8889	295.092547

Dependent Variable: hhv

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	2264282358	566070589	6859.32	<.0001
Error	40	3301030	82526		
Corrected Total	44	2267583388			

R-Square	Coeff Var	Root MSE	HHV Mean
0.998544	1.164602	287.2730	24667.04

Source	DF	Anova SS	Mean Square	F Value	Pr > F
temp	4	2264282358	566070589	6859.32	<.0001

Table C.4.2. Data for ash content of bio-char (refer Table 16).

Comp. (%)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
0	1	14.2744	14.2744	16.8481	2.5737	14.2828	0.0084	0.3264
	2	14.4946	14.4949	16.1933	1.6984	14.508	0.0131	0.7713
	3	14.8899	14.89	16.2675	1.3775	14.896	0.006	0.4356
5	1	15.4959	15.4945	16.0642	0.5697	15.5437	0.0492	8.6361
	2	14.433	14.4307	15.0677	0.637	14.486	0.0553	8.6813
	3	14.7359	14.7354	15.301	0.5656	14.7883	0.0529	9.3529
10	1	14.9383	14.938	15.6071	0.6691	15.0349	0.0969	14.4821
	2	14.9759	14.9747	15.6294	0.6547	15.0658	0.0911	13.9148
	3	14.3652	14.3651	14.9548	0.5897	14.4374	0.0723	12.2605
15	1	15.1829	15.1814	15.7856	0.6042	15.2721	0.0907	15.0116
	2	14.132	14.1307	14.865	0.7343	14.2469	0.1162	15.8246
	3	14.2177	14.2168	14.857	0.6402	14.328	0.1112	17.3696
100	1	14.2743	14.2739	15.8913	1.6174	15.154	0.8801	54.4145
	2	14.4892	14.489	15.8304	1.3414	15.2884	0.7994	59.5945
	3	14.8947	14.8935	16.3717	1.4782	15.784	0.8905	60.2422

Comp. (%)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
0	1	14.5028	14.5033	16.7285	2.2252	14.5095	0.0062	0.2786
	2	14.6681	14.6683	16.3004	1.6321	14.6815	0.0132	0.8088
	3	15.4717	15.4719	17.0858	1.6139	15.4792	0.0073	0.4523
5	1	14.7453	14.7443	15.4449	0.7006	14.7961	0.0518	7.3937
	2	13.7297	13.7294	14.4094	0.68	13.7867	0.0573	8.4265
	3	15.3547	15.354	16.0192	0.6652	15.4207	0.0667	10.0271
10	1	12.9908	12.9889	13.8567	0.8678	13.1212	0.1323	15.2454
	2	12.8992	12.8969	13.3957	0.4988	12.9585	0.0616	12.3496
	3	15.1231	15.1214	15.6927	0.5713	15.1902	0.0688	12.0427
15	1	14.3473	14.3473	14.9707	0.6234	14.4482	0.1009	16.1854
	2	15.0052	15.005	15.762	0.757	15.1312	0.1262	16.6711
	3	15.1393	15.1386	15.7824	0.6438	15.2376	0.099	15.3774
100	1	14.5049	14.5036	15.9767	1.4731	15.33	0.8264	56.0994
	2	14.6652	14.6643	16.0283	1.364	15.4794	0.8151	59.7581
	3	15.4697	15.4681	16.9575	1.4894	16.3844	0.9163	61.5214

Comp. (%)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
0	1	14.2744	14.2744	16.1294	1.855	14.2798	0.0054	0.2911
	2	14.4946	14.4949	16.2369	1.742	14.5085	0.0136	0.7807
	3	14.8899	14.89	16.7456	1.8556	14.8977	0.0077	0.4150
5	1	15.4957	15.4943	16.0351	0.5408	15.536	0.041	7.6368
	2	14.4327	14.4304	14.5217	0.0913	14.439	0.008	9.0909
	3	14.7359	14.7354	16.0284	1.293	14.86	0.125	9.6365
10	1	14.9382	14.9379	15.8134	0.8755	15.07	0.132	15.0999
	2	14.9754	14.9742	15.685	0.7108	15.065	0.091	12.7743
	3	14.3648	14.3647	15.7914	1.4267	14.551	0.186	13.0371

Comp. (%)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
15	1	15.1827	15.1812	16.0985	0.9173	15.319	0.138	15.0332
	2	14.1318	14.1305	16.0517	1.9212	14.421	0.291	15.1260
	3	14.2177	14.2168	16.0922	1.8754	14.52	0.303	16.1459
100	1	14.2743	14.2739	15.0015	0.7276	14.683	0.4091	56.2259
	2	14.4892	14.489	15.1256	0.6366	14.869	0.38	59.6921
	3	14.8947	14.8935	15.4569	0.5634	15.2391	0.3456	61.3419

SAS code for ash content of bio-char:

```
data obj2;
input temp ash;
datalines;
0      0.326378366
0      0.771314178
0      0.435571688
0      0.27862664
0      0.808773972
0      0.452320466
0      0.291105121
0      0.780711825
0      0.414960121
5      8.636124276
5      8.681318681
5      9.352899576
10     14.48214019
10     13.91477012
10     12.26047143
15     15.01158557
15     15.82459485
15     17.36957201
5      7.393662575
5      8.426470588
5      10.02705953
10     15.24544826
10     12.34963913
10     12.04270961
15     16.18543471
15     16.67107001
15     15.37744641
5      7.63683432
5      9.090909091
5      9.636504254
10     15.09994289
10     12.77433877
10     13.03707857
```

```
15    15.03324975
15    15.12596294
15    16.14588888
100   54.4144924
100   59.59445356
100   60.24218644
100   56.09938226
100   59.75806452
100   61.52141802
100   56.22594832
100   59.69211436
100   61.34185304
;
run;
proc anova data=obj2;
class temp;
model ash=temp;
means temp/ alpha=0.05;
run;
```

SAS result for ash content of bio-char:

```
                                The ANOVA Procedure

                 Level of          -------------ash-------------
                 temp         N             Mean          Std Dev

                 0            9        0.5066403       0.21903164
                 5            9        8.7646425       0.87290415
                 10           9       13.4673932       1.24788865
                 15           9       15.8605339       0.81398132
                 100          9       58.7655459       2.53557237

Dependent Variable: Ash

                                             Sum of
      Source                      DF        Squares     Mean Square    F Value    Pr > F

      Model                        4    18606.71796      4651.67949    2458.90    <.0001

      Error                       40       75.67084         1.89177

      Corrected Total             44    18682.38881


                      R-Square     Coeff Var      Root MSE      ash Mean

                      0.995950      7.063216      1.375417      19.47295


      Source                      DF       Anova SS     Mean Square    F Value    Pr > F

      temp                         4    18606.71796      4651.67949    2458.90    <.0001
```

Table C.4.3. Data for moisture content of bio-char (refer Table 16).

Comp. (%)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
0	1	96.9211	100.3934	3.4723	100.2735	3.3524	0.1199	3.45
	2	93.5845	97.114	3.5295	96.969	3.3845	0.145	4.11
	3	152.4772	156.1768	3.6996	156.0545	3.5773	0.1223	3.31
5	1	43.4977	45.4427	1.945	45.3859	1.8882	0.0568	2.92
	2	42.9453	45.2951	2.3498	45.2317	2.2864	0.0634	2.70
	3	43.2437	45.3121	2.0684	45.2663	2.0226	0.0458	2.21
10	1	42.1079	44.5818	2.4739	44.5087	2.4008	0.0731	2.95
	2	46.1818	48.4822	2.3004	48.429	2.2472	0.0532	2.31
	3	44.6902	47.2155	2.5253	47.1406	2.4504	0.0749	2.97
15	1	44.359	46.8085	2.4495	46.7457	2.3867	0.0628	2.56
	2	48.2318	50.5035	2.2717	50.4301	2.1983	0.0734	3.23
	3	45.566	48.1417	2.5757	48.0535	2.4875	0.0882	3.42
100	1	47.5009	51.7488	4.2479	51.5616	4.0607	0.1872	4.41
	2	46.8336	51.2526	4.419	51.0802	4.2466	0.1724	3.90
	3	46.0423	50.1707	4.1284	50.0563	4.014	0.1144	2.77

Comp. (%)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
0	1	92.085	95.7132	3.6282	95.5872	3.5022	0.126	3.47
	2	113.0288	116.7161	3.6873	116.5723	3.5435	0.1438	3.90
	3	121.4935	125.0328	3.5393	124.9066	3.4131	0.1262	3.57
5	1	46.16	48.8331	2.6731	48.742	2.582	0.0911	3.41
	2	45.4183	47.5671	2.1488	47.5158	2.0975	0.0513	2.39
	3	44.0163	46.2906	2.2743	46.2356	2.2193	0.055	2.42
10	1	45.769	48.4783	2.7093	48.4052	2.6362	0.0731	2.70
	2	46.02	48.2538	2.2338	48.1957	2.1757	0.0581	2.60
	3	46.7842	48.9034	2.1192	48.8383	2.0541	0.0651	3.07
15	1	41.7889	43.7882	1.9993	43.733	1.9441	0.0552	2.76
	2	47.5748	49.6954	2.1206	49.6317	2.0569	0.0637	3.00
	3	48.3651	50.5124	2.1473	50.4423	2.0772	0.0701	3.26
100	1	45.5664	49.2776	3.7112	49.1078	3.5414	0.1698	4.58
	2	43.1856	47.2647	4.0791	47.112	3.9264	0.1527	3.74
	3	46.941	51.5296	4.5886	51.4022	4.4612	0.1274	2.78

Comp. (%)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
0	1	96.9211	100.1032	3.1821	99.9874	3.0663	0.1158	3.64
	2	93.5845	97.2567	3.6722	97.1168	3.5323	0.1399	3.81
	3	152.4772	155.8759	3.3987	155.7569	3.2797	0.119	3.50
5	1	43.4984	45.5853	2.0869	45.5172	2.0188	0.0681	3.26
	2	42.9455	44.2426	1.2971	44.2093	1.2638	0.0333	2.57
	3	43.2441	44.6384	1.3943	44.6044	1.3603	0.034	2.44
10	1	42.108	43.3177	1.2097	43.2807	1.1727	0.037	3.06
	2	46.1818	47.1754	0.9936	47.1492	0.9674	0.0262	2.64
	3	44.6913	45.8471	1.1558	45.8096	1.1183	0.0375	3.24
15	1	44.3598	45.648	1.2882	45.6129	1.2531	0.0351	2.72
	2	48.2322	50.0966	1.8644	50.0408	1.8086	0.0558	2.99
	3	45.5663	46.5522	0.9859	46.5144	0.9481	0.0378	3.83
100	1	47.5009	51.7969	4.296	51.5998	4.0989	0.1971	4.59
	2	46.8336	51.2003	4.3667	51.0411	4.2075	0.1592	3.65
	3	46.0423	50.1189	4.0766	50.0048	3.9625	0.1141	2.80

SAS code for moisture content of bio-char:

```
data obj2;
input temp moisture;
datalines;
0       3.453042652
0       4.108230628
0       3.305762785
0       3.472796428
0       3.899872535
0       3.565676829
0       3.639106251
0       3.809705354
0       3.501338747
5       2.920308483
5       2.698101966
5       2.214271901
10      2.95484862
10      2.31264128
10      2.965984239
15      2.563788528
15      3.231060439
15      3.424311838
5       3.408028132
5       2.387379002
5       2.418326518
10      2.698113904
10      2.600949055
10      3.07191393
15      2.760966338
15      3.00386683
15      3.264564802
5       3.263213379
5       2.567265438
5       2.438499606
10      3.058609573
10      2.636876006
10      3.24450597
15      2.724732184
15      2.992919974
15      3.83406025
100     4.406883401
100     3.901335144
100     2.771049317
100     4.575339513
100     3.743472825
100     2.776445975
100     4.587988827
100     3.645773696
100     2.798901045
;
run;
proc anova data=obj2;
class temp;
model moisture=temp;
means temp/ alpha=0.05;
```

```
run;
```

SAS result for moisture content of bio-char:

The ANOVA Procedure

Level of temp	N	moisture Mean	moisture Std Dev
0	9	3.63950358	0.25370939
5	9	2.70171049	0.41322373
10	9	2.83827140	0.29387034
15	9	3.08891902	0.39547063
100	9	3.68968775	0.76048648

Dependent Variable: Moisture

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	7.41676712	1.85419178	8.78	<.0001
Error	40	8.44975023	0.21124376		
Corrected Total	44	15.86651735			

R-Square	Coeff Var	Root MSE	moisture Mean
0.467448	14.40061	0.459613	3.191618

Source	DF	Anova SS	Mean Square	F Value	Pr > F
temp	4	7.41676712	1.85419178	8.78	<.0001

APPENDIX D

SUPPLEMENTARY DATA FOR SELECTED FIGURES AND TABLES INVOLVED IN PRODUCTION OF BIO-OIL USING CASCADE PYROLYSIS REACTOR

This appendix comprises of all the data, SAS code and SAS results involved in constructing the figures (Figure 31-33) and tables (Table17-19) of the second specific objective of this work. Data tables shown below represents the yield of bio-oil, char and gas and their physical properties, obtained while operating the respective biomass at selected temperatures.

D.1 EFFECT OF TEMPERATURE ON PRODUCT YIELD

Table D.1.1. Data for yield of bio-oil obtained from selected biomass at different temperatures (refer Figure 31).

Operating temperature (°C)	Iteration No.	Product yield (wt. %)		
		Bio-oil	Bio-char	Bio-char
300	1	14.0	79.6	6.4
	2	14.0	78.2	7.8
	3	14.9	76.4	8.7
500	1	24.6	27.1	48.3
	2	25.2	26.8	48.0
	3	26.2	26.2	47.7

SAS code for pine wood bio-oil (refer Table 17):

```
data obj3;
input temp oilyield;
datalines;
300    14
300    14
300    14.88888889
500    24.61538462
500    25.23076923
500    26.15384615
;
run;
```

```
proc anova data=obj3;
class temp;
model oilyield=temp;
means temp/ alpha=0.05;
run;
quit;
proc boxplot data=obj3;
plot oilyield*temp /boxstyle=schematic;
run;
```

SAS result for pine wood bio-oil (refer Table 17):

```
                              The ANOVA Procedure

                     Level of         -----------oilyield----------
                     temp        N             Mean          Std Dev

                     300         3       14.2962963       0.51320024
                     500         3       25.3333333       0.77434199

Dependent Variable: oilyield

                                            Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        1     182.7242798     182.7242798     423.47    <.0001

      Error                        4       1.7259600       0.4314900

      Corrected Total              5     184.4502398


                    R-Square     Coeff Var      Root MSE    oilyield Mean

                    0.990643      3.315090      0.656879         19.81481


      Source                      DF         Anova SS    Mean Square    F Value    Pr > F

      temp                         1     182.7242798     182.7242798     423.47    <.0001
```

SAS code for pine wood bio-char (refer Table 17):

```
data obj3;
input temp charyield;
datalines;
300   79.55555556
300   78.22222222
300   76.44444444
500   27.07692308
500   26.76923077
500   26.15384615
;
run;
proc anova data=obj3;
class temp;
model charyield=temp;
```

```
means temp/ alpha=0.05;
run;
quit;
proc boxplot data=obj3;
plot charyield*temp /boxstyle=schematic;
run;
```

SAS result for pine wood bio- char (refer Table 17):

```
                              The ANOVA Procedure

                        Level of          ----------charyield----------
                        temp          N             Mean          Std Dev

                        300           3       78.0740741       1.56083760
                        500           3       26.6666667       0.47000777

Dependent Variable: charyield

                                                Sum of
      Source                      DF           Squares     Mean Square    F Value    Pr > F

      Model                        1       3964.082304     3964.082304    2983.74    <.0001

      Error                        4          5.314243        1.328561

      Corrected Total              5       3969.396547


                      R-Square     Coeff Var      Root MSE    charyield Mean

                      0.998661      2.200924      1.152632          52.37037


      Source                      DF          Anova SS     Mean Square    F Value    Pr > F

      temp                         1       3964.082304     3964.082304    2983.74    <.0001
```

SAS code for pine wood gas (refer Table 17):

```
data obj3;
input temp gasyield;
datalines;
300   6.444444444
300   7.777777778
300   8.666666667
500   48.30769231
500   48
500   47.69230769
;
run;
proc anova data=obj3;
class temp;
model gasyield=temp;
means temp/ alpha=0.05;
run;
```

```
quit;
proc boxplot data=obj3;
plot gasyield*temp /boxstyle=schematic;
run;
```

SAS result for pine wood gas (refer Table 17):

```
                          The ANOVA Procedure

                 Level of          -----------gasyield----------
                 temp         N             Mean          Std Dev

                 300          3        7.6296296       1.11849399
                 500          3       48.0000000       0.30769231

Dependent Variable: gasyield

                                             Sum of
      Source                      DF        Squares     Mean Square    F Value    Pr > F

      Model                        1    2444.650206     2444.650206    3633.27    <.0001

      Error                        4       2.691407        0.672852

      Corrected Total              5    2447.341612


                 R-Square     Coeff Var      Root MSE    gasyield Mean

                 0.998900      2.949059      0.820275         27.81481


      Source                      DF       Anova SS     Mean Square    F Value    Pr > F

      temp                         1    2444.650206     2444.650206    3633.27    <.0001
```

Table D.1.2. Data for comparison of bio-oil yield obtained from single stage and 2-stage process (refer Figure 32).

Operating temperature (°C)	Iteration No.	Total bio-oil yield (wt. %)
Single stage	1	37.6
	2	36.4
	3	39.4
2-Stage	1	38.6
	2	39.2
	3	41.1

SAS code for pine wood bio-oil (refer Table 17):

```
data obj3;
input temp oilyield;
datalines;
300   14
300   14
300   14.88888889
500   24.61538462
500   25.23076923
500   26.15384615
;
run;
proc anova data=obj3;
class temp;
model oilyield=temp;
means temp/ alpha=0.05;
run;
quit;
proc boxplot data=obj3;
plot oilyield*temp /boxstyle=schematic;
run;
```

SAS result for pine wood bio-oil (refer Table 17):

The ANOVA Procedure

Level of temp	N	oilyield Mean	oilyield Std Dev
300	3	14.2962963	0.51320024
500	3	25.3333333	0.77434199

Dependent Variable: oilyield

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	182.7242798	182.7242798	423.47	<.0001
Error	4	1.7259600	0.4314900		
Corrected Total	5	184.4502398			

R-Square	Coeff Var	Root MSE	oilyield Mean
0.990643	3.315090	0.656879	19.81481

Source	DF	Anova SS	Mean Square	F Value	Pr > F
temp	1	182.7242798	182.7242798	423.47	<.0001

D.2 EFFECT OF TEMPERATURE ON PHYSICAL PROPERTIES OF BIO-OIL

Table D.2.1. Data for density of pinewood bio-oil (refer Table 18).

Temp (°C)	Iteration No.	Sample #1				Sample #2				Sample #3			
		Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)	Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)	Weight of the beaker (g)	Weight of the beaker with bio-oil (g)	Wt. of the oil (g)	Density (kg/m^3)
Single stage	1	5.7391	7.9807	2.2416	1120.8	5.818	8.0104	2.1924	1096.2	5.7492	8.0101	2.2609	1130.45
	2	5.7511	8.0867	2.3356	1167.8	5.7514	8.0567	2.3053	1152.65	5.8874	8.1847	2.2973	1148.65
	3	5.7589	8.0115	2.2526	1126.3	5.7563	8.01	2.2537	1126.85	5.7554	7.9898	2.2344	1117.2
2-stage	1	5.7367	7.9999	2.2632	1131.6	5.7451	8.0187	2.2736	1136.8	5.7389	8	2.2611	1130.55
	2	5.7391	8.0009	2.2618	1130.9	5.8167	8.114	2.2973	1148.65	5.7512	8.0021	2.2509	1125.45
	3	5.7416	8.0046	2.263	1131.5	5.7423	8.0076	2.2653	1132.65	5.7376	8.0079	2.2703	1135.15

SAS code for density of pine wood bio-oil:

```
data obj3;
input temp density;
datalines;
1       1120.8
1       1167.8
1       1126.3
1       1096.2
1       1152.65
1       1126.85
1       1130.45
1       1148.65
1       1117.2
2       1131.6
2       1130.9
2       1131.5
2       1136.8
2       1148.65
2       1132.65
2       1130.55
2       1125.45
2       1135.15
;
run;
proc anova data=obj3;
class temp;
model density=temp;
means temp/ alpha=0.05;
run;
```

The ANOVA Procedure

Level of temp	N	density Mean	density Std Dev
1	9	1131.87778	21.4262851
2	9	1133.69444	6.4361501

Dependent Variable: density

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	14.851250	14.851250	0.06	0.8106
Error	16	4004.077778	250.254861		
Corrected Total	17	4018.929028			

R-Square	Coeff Var	Root MSE	density Mean
0.003695	1.396508	15.81945	1132.786

Source	DF	Anova SS	Mean Square	F Value	Pr > F

```
temp                        1      14.85125000      14.85125000       0.06    0.8106
```

Table D.2.2. Data for acidity (pH) of pine wood bio-oil (refer Table 18).

Operating temperature (°C)	Iteration No.	Sample # 1	Sample # 2	Sample # 3
Single stage	1	3.68	3.69	3.7
	2	3.74	3.73	3.73
	3	3.76	3.76	3.76
2-stage	1	3.88	3.88	3.88
	2	3.89	3.79	3.79
	3	3.74	3.74	3.76

SAS code for acidity of pine wood bio-oil:

```
data obj3;
input temp pH;
datalines;
1       3.68
1       3.74
1       3.76
1       3.69
1       3.73
1       3.76
1       3.7
1       3.73
1       3.76
2       3.88
2       3.89
2       3.74
2       3.88
2       3.79
2       3.74
2       3.88
2       3.79
2       3.76
;
run;
proc anova data=obj3;
class temp;
model pH=temp;
means temp/ alpha=0.05;
run;
```

```
                        The ANOVA Procedure

          Level of          --------------pH-------------
          temp          N             Mean           Std Dev
```

```
                    1            9       3.72777778       0.03113590

                    2            9       3.81666667       0.06500000
```

```
Dependent Variable: pH
                                             Sum of
     Source                      DF          Squares     Mean Square    F Value    Pr > F
     Model                        1       0.03555556      0.03555556      13.69    0.0019
     Error                       16       0.04155556      0.00259722
     Corrected Total             17       0.07711111

                    R-Square     Coeff Var      Root MSE       pH Mean
                    0.461095      1.351006      0.050963      3.772222

     Source                      DF         Anova SS     Mean Square    F Value    Pr > F
     temp                         1           0.03555556      0.03555556      13.69    0.0019
```

Table D.2.3. Data for water content of pine wood bio-oil (refer Table 18).

Sample	Sample wt (g)		Difference (g)	KFR vol (ml)		Difference (ml)	Water (wt%)
	Initial	Final		Initial	final		
methanol	0.0000	2.4000	2.4000				40ml
water			5 µl	0.0000	1.4000	1.400	3.57
water			5 µl	1.4000	2.8000	1.400	3.57
single-1a	155.1438	155.0818	0.0620	0	2.2	2.2	19.71
single -1b	155.0818	155.0151	0.0667	2.2	4.2	2	16.65
single -1c	155.0151	154.9532	0.0619	4.2	6.2	2	17.95
single -2a	156.7217	156.6661	0.0556	6.2	8.0	1.8	17.98
single -2b	156.6650	156.6237	0.0413	8.0	9.6	1.6	21.52
single -2c	156.6237	156.5786	0.0451	9.6	11.3	1.7	20.94
single -3a	164.8720	164.8252	0.0468	11.3	13.0	1.7	20.18
single -3b	164.8252	164.7893	0.0359	13.0	14.3	1.3	20.11
single -3c	164.7893	164.7491	0.0402	14.3	15.9	1.6	22.11
2s-500-1a	70.5118	70.4327	0.0791	8.4	11.7	3.3	14.90
2s-500-1b	70.43	70.3784	0.0516	11.7	14.1	2.4	16.61
2s-500-1c	70.3114	70.2581	0.0533	14.1	16.4	2.3	15.41
2s-500-2a	72.6765	72.6136	0.0629	16.4	18.8	2.4	13.63
2s-500-2b	72.61	72.5564	0.0536	18.8	20.5	1.7	11.33
2s-500-2c	72.5536	72.5014	0.0522	20.5	22.5	2	13.68
2s-500-3a	70.6941	70.6442	0.0499	0	2.2	2.2	15.75
2s-500-3b	70.6435	70.5943	0.0492	2.2	4.1	1.9	13.79
2s-500-3c	70.5921	70.5463	0.0458	4.1	5.9	1.8	14.04

SAS code for water content of pine wood bio-oil:

```
data obj3;
input temp water;
datalines;
1       19.20124424
1       19.88863962
1       22.15892877
1       20.00365303
1       19.37986047
1       18.62198883
1       19.28177007
1       18.86793962
1       14.76560797
2       14.899767
2       16.61129767
2       15.4114197
2       13.62707409
2       11.32729347
2       13.68363602
2       15.74577916
2       13.79210386
2       14.03618384
;
run;
proc anova data=obj3;
class temp;
model water=temp;
means temp/ alpha=0.05;
run;
```

The ANOVA Procedure

Level of temp	N	water Mean	water Std Dev
1	9	19.1299592	1.93579512
2	9	14.3482839	1.54125119

Dependent Variable: water

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	102.8898846	102.8898846	33.61	<.0001
Error	16	48.9820640	3.0613790		
Corrected Total	17	151.8719486			

R-Square	Coeff Var	Root MSE	water Mean
0.677478	10.45264	1.749680	16.73912

```
Source                      DF        Anova SS     Mean Square    F Value    Pr > F

temp                         1     102.8898846     102.8898846      33.61    <.0001
```

Table D.2.4. Data for higher heating value of pine wood bio-oil (refer Table 18).

Operating temperature (°C)	Iteration No.	Weight of the sample #1	Energy required (J/g)	Weight of the sample #2	Energy required (J/g)	Weight of the sample #3	Energy required (J/g)
Single stage	1	0.5683	21333	0.5462	21268	0.5183	21424
	2	0.654	22270	0.5483	22238	0.5032	22309
	3	0.5	22368	0.6093	22472	0.5333	22461
2-stage	1	0.5006	20274	0.5023	20216	0.4932	20103
	2	0.6725	20969	0.5882	20741	0.5712	20768
	3	0.5137	19871	0.5576	19627	0.5474	19899

SAS code for higher heating value of pine wood bio-oil:

```
data obj3;
input temp HHV;
datalines;
1      21333
1      22270
1      22368
1      21268
1      22238
1      22472
1      21424
1      22309
1      22461
2      20274
2      20969
2      19871
2      20216
2      20741
2      19627
2      20103
2      20768
2      19899
;
run;
proc anova data=obj3;
class temp;
model HHV=temp;
means temp/ alpha=0.05;
run;
```

```
                          The ANOVA Procedure

              Level of          -------------HHV-------------
              temp          N           Mean          Std Dev
```

```
                        1              9       22015.8889       513.075395
                        2              9       20274.2222       460.895535

Dependent Variable: HHV
                                                  Sum of
      Source                      DF             Squares     Mean Square    F Value    Pr > F
      Model                        1         13650312.50     13650312.50      57.39    <.0001
      Error                       16          3805368.44       237835.53
      Corrected Total             17         17455680.94

                        R-Square     Coeff Var      Root MSE      HHV Mean
                        0.781998      2.306373      487.6838      21145.06

      Source                      DF            Anova SS     Mean Square    F Value    Pr > F
      temp                         1         13650312.50     13650312.50      57.39    <.0001
```

Table D.2.5. Data for ash content of pine wood bio-oil (refer Table 18).

Temp (°C)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
Single stage	1	14.2752	14.2747	16.927	2.6523	14.2799	0.0052	0.1961
	2	14.4982	14.4972	17.8152	3.318	14.5091	0.0119	0.3586
	3	14.8937	14.8931	17.4977	2.6046	14.9042	0.0111	0.4262
2-stage	1	14.9378	14.9378	16.574	1.6362	14.9498	0.012	0.7334
	2	14.3761	14.3744	16.8722	2.4978	14.3935	0.0191	0.7647
	3	14.3651	14.3645	16.0978	1.7333	14.3707	0.0062	0.3577

Temp (°C)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
Single stage	1	14.5044	14.5033	17.2331	2.7298	14.5084	0.0051	0.1868
	2	16.6669	16.666	17.9489	1.2829	16.6708	0.0048	0.3742
	3	15.4693	15.4689	18.1079	2.639	15.4805	0.0116	0.4396
2-stage	1	12.9887	12.9886	14.2167	1.2281	12.9976	0.009	0.7328
	2	12.8979	12.8967	15.0905	2.1938	12.9139	0.0172	0.7840
	3	15.1211	15.1208	16.8534	1.7326	15.1272	0.0064	0.3694

Temp (°C)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
Single stage	1	14.2755	14.2745	15.5529	1.2784	14.2772	0.0027	0.2112
	2	14.4982	14.4975	15.8659	1.3684	14.5021	0.0046	0.3362
	3	14.8938	14.893	16.2628	1.3698	14.8992	0.0062	0.4526
2-stage	1	14.9398	14.9378	15.6492	0.7114	14.9431	0.0053	0.7450
	2	14.3750	14.3744	16.4511	2.0767	14.3909	0.0165	0.7945
	3	14.3653	14.3651	16.1085	1.7434	14.3711	0.006	0.3442

SAS code for ash content of pine wood bio-oil:

```
data obj3;
input temp Ash;
datalines;
1       0.196056253
1       0.358649789
1       0.426169085
1       0.186826874
1       0.374152311
1       0.43956044
1       0.211201502
1       0.336159018
1       0.452620821
2       0.733406674
2       0.764672912
2       0.357699187
2       0.732839345
2       0.784027714
2       0.369387048
2       0.74500984
2       0.794529783
2       0.344155099
;
run;
proc anova data=obj3;
class temp;
model Ash=temp;
means temp/ alpha=0.05;
run;
```

```
                The ANOVA Procedure

                        Level of          -------------Ash-------------
                        temp         N            Mean          Std Dev

                        1            9      0.33126623       0.10702461
                        2            9      0.62508084       0.20217068
```

```
Dependent Variable: Ash

                                            Sum of
      Source                      DF       Squares     Mean Square    F Value    Pr > F

      Model                        1    0.38847162      0.38847162      14.85    0.0014

      Error                       16    0.41861803      0.02616363

      Corrected Total             17    0.80708964


                     R-Square     Coeff Var      Root MSE      Ash Mean

                     0.481324      33.82700      0.161752      0.478174


      Source                      DF      Anova SS     Mean Square    F Value    Pr > F

      temp                         1    0.38847162      0.38847162      14.85    0.0014
```

Table D.2.6. Data for solid content of pine wood bio-oil (refer Table 18).

Operating temperature (°C)	Iteration No.	Sample #1				
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of the oil (g)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
Single stage	1	320.5	312.4	1.0165	314.7	0.23
	2	321.7	313.4	1.0072	320.1	0.67
	3	324.7	316.4	1.0029	324.6	0.82
2-stage	1	330.1	322	1.0283	337.9	1.55
	2	328.8	320.1	1.0167	332.7	1.24
	3	326.7	318.3	1.0182	335	1.64

Operating temperature (°C)	Iteration No.	Sample #2				
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of the oil (g)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
Single stage	1	322.6	314.4	1.001	317.1	0.27
	2	323.9	315.6	1.0286	323.3	0.75
	3	330	320.5	1.0024	329	0.85
2-stage	1	325.3	318.5	1.0222	332.1	1.33
	2	327.8	319.4	0.9951	330.4	1.11
	3	328.8	319	1.0118	333.9	1.47

Operating temperature (°C)	Iteration No.	Sample #3				
		Weight of filter paper (mg)	Weight of filter paper after drying (mg)	Weight of the oil (g)	Weight of filter paper after test (mg)	Wt. of solid (wt. %)
Single stage	1	330.2	321.7	0.9994	324.6	0.29
	2	330.9	322.4	0.9812	329.4	0.71
	3	339.1	331.5	1.0269	339.3	0.76
2-stage	1	321.7	313.4	0.9989	327.4	1.40
	2	329.9	319.7	1.0004	331.1	1.14
	3	329.1	318.1	1.0025	332.6	1.45

SAS code for solid content of pine wood bio-oil:

```
data obj3;
input temp Solid;
datalines;
1       0.226266601
1       0.665210485
1       0.817628876
1       0.26973027
1       0.748590317
1       0.847964884
1       0.290174104
1       0.713412148
1       0.759567631
2       1.546241369
2       1.239303629
2       1.640149283
2       1.330463706
2       1.105416541
2       1.472623048
2       1.401541696
2       1.139544182
2       1.44638404
;
run;
proc anova data=obj3;
class temp;
model Solid=temp;
means temp/ alpha=0.05;
run;
```

SAS result for solid content of pine wood bio-oil:

```
                              The ANOVA Procedure

               Level of          ------------Solid-----------
               temp        N             Mean            Std Dev
```

```
                   1            9       0.59317170       0.25441888
                   2            9       1.36907417       0.18136765

Dependent Variable: Solid
                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F
      Model                        1      2.70911085      2.70911085      55.50    <.0001
      Error                       16      0.78098553      0.04881160
      Corrected Total             17      3.49009638

                 R-Square     Coeff Var      Root MSE    Solid Mean
                 0.776228      22.51843      0.220933      0.981123


      Source                      DF        Anova SS     Mean Square    F Value    Pr > F
      temp                         1      2.70911085      2.70911085      55.50    <.0001
```

D.3 VISCOSITY ANALYSIS OF DIFFERENT BIO-OILS

Table D.3.1. Data for Figure 32

P.W at 300°C (1st stage)			
Shear Stress (Pa)	Shear Rate (1/s)	Viscosity (Pas)	Log(Viscosity)
0.01	0.040	0.23	-0.63884
0.05	2.656	0.02	-1.73384
0.12	4.863	0.02	-1.61439
0.10	7.659	0.01	-1.8788
0.07	11.090	0.01	-2.19266
0.10	13.164	0.01	-2.10321
0.13	16.527	0.01	-2.11966
0.10	19.112	0.01	-2.28583
0.12	22.176	0.01	-2.25159
0.14	25.147	0.01	-2.26947
0.13	28.099	0.00	-2.32544
0.14	30.915	0.00	-2.34728
0.15	33.781	0.00	-2.34984
0.15	36.769	0.00	-2.3897
0.16	39.625	0.00	-2.39254
0.18	42.600	0.00	-2.38609
0.18	45.551	0.00	-2.41149
0.19	48.405	0.00	-2.40338
0.20	51.329	0.00	-2.4143
0.20	54.385	0.00	-2.44006
0.22	57.442	0.00	-2.41977
0.22	60.313	0.00	-2.43394
0.24	63.214	0.00	-2.41766
0.23	66.185	0.00	-2.45187

P.W at 300°C (1st stage)			
Shear Stress (Pa)	Shear Rate (1/s)	Viscosity (Pas)	Log(Viscosity)
0.25	69.242	0.00	-2.44069
0.25	72.179	0.00	-2.45308
0.26	75.130	0.00	-2.4602
0.27	78.062	0.00	-2.45357
0.29	81.058	0.00	-2.44585
0.29	83.970	0.00	-2.45822
0.29	86.942	0.00	-2.47808
0.31	89.810	0.00	-2.46745
0.33	92.493	0.00	-2.45296
0.33	95.399	0.00	-2.46199
0.31	98.393	0.00	-2.49852

P.W at 500°C (2nd stage)			
Shear Stress (Pa)	Shear Rate (1/s)	Viscosity (Pas)	Log(Viscosity)
0.01	0.044	0.20	-0.71
0.15	2.035	0.07	-1.14
0.18	5.461	0.03	-1.48
0.14	7.392	0.02	-1.73
0.17	10.720	0.02	-1.81
0.14	13.549	0.01	-1.98
0.15	16.141	0.01	-2.03
0.18	18.892	0.01	-2.02
0.20	22.220	0.01	-2.05
0.21	25.379	0.01	-2.08
0.21	28.689	0.01	-2.13
0.21	30.980	0.01	-2.16
0.37	33.585	0.01	-2.19
0.39	36.438	0.01	-2.19
0.39	37.226	0.00	-2.21
0.41	41.141	0.01	-2.21
0.42	47.055	0.01	-2.21
0.45	47.934	0.01	-2.20
0.47	49.916	0.01	-2.20
0.48	52.948	0.01	-2.21
0.50	56.476	0.01	-2.21
0.52	59.950	0.01	-2.20
0.57	63.133	0.01	-2.18
0.56	66.123	0.01	-2.20
0.56	68.964	0.01	-2.22
0.59	71.657	0.01	-2.21

P.W at 500°C (2nd stage)			
Shear Stress (Pa)	Shear Rate (1/s)	Viscosity (Pas)	Log(Viscosity)
0.61	74.589	0.01	-2.21
0.01	77.595	0.01	-0.71
0.15	80.520	0.01	-1.14
0.18	83.187	0.01	-1.48
0.14	86.156	0.01	-1.73
0.17	89.361	0.01	-1.81
0.14	92.736	0.01	-1.98
0.15	95.697	0.01	-2.03
0.18	98.555	0.01	-2.02

D.4 EFFECT OF TEMPERATURE ON PHYSICAL PROPERTIES OF BIO-CHAR

Table D.4.1. Data for higher heating value of pine wood bio-char (refer Table 19).

Operating temperature (°C)	Iteration No.	Weight of the sample #1	Energy required (J/g)	Weight of the sample #2	Energy required (J/g)	Weight of the sample #3	Energy required (J/g)
Single stage	1	0.4819	30234	0.4862	30191	0.6028	30124
	2	0.6459	30239	0.5521	30248	0.5696	30272
	3	0.513	30901	0.5189	30862	0.6452	31007
2-stage	1	0.4961	31404	0.4816	31478	0.5048	31513
	2	0.52	31832	0.5218	31761	0.6331	31814
	3	0.5593	31928	0.5029	31871	0.5538	31933

SAS code for higher heating value of pine wood bio-char:

```
data obj3;
input temp HHV;
datalines;
1       30234
1       30239
1       30901
1       30191
1       30248
1       30862
1       30124
1       30272
1       31007
2       31404
2       31832
2       31928
2       31478
2       31761
2       31871
2       31513
```

```
2       31814
2       31933
;
run;
proc anova data=obj3;
class temp;
model HHV=temp;
means temp/ alpha=0.05;
run;
```

```
                                    The ANOVA Procedure

                       Level of          -------------HHV-------------
                       temp          N            Mean          Std Dev

                       1             9      30453.1111       357.128984
                       2             9      31726.0000       204.768162

Dependent Variable: HHV

                                                Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F

      Model                        1      7291107.556     7291107.556      86.05    <.0001

      Error                       16      1355768.889       84735.556

      Corrected Total             17      8646876.444


                      R-Square     Coeff Var      Root MSE      HHV Mean
                      0.843207      0.936307      291.0937      31089.56


      Source                      DF         Anova SS     Mean Square    F Value    Pr > F
      temp                         1      7291107.556     7291107.556      86.05    <.0001
```

Table D.4.2. Data for ash content of pine wood bio-char (refer Table 19).

Temp (°C)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
Single stage	1	14.2744	14.2744	16.8481	2.5737	14.2828	0.0084	0.3264
	2	14.4946	14.4949	16.1933	1.6984	14.508	0.0131	0.7713
	3	14.8899	14.89	16.2675	1.3775	14.896	0.006	0.4356
2-stage	1	14.2755	14.2755	14.9353	0.6598	14.2916	0.0161	2.4401
	2	14.4985	14.4981	15.2522	0.7541	14.5117	0.0136	1.8035
	3	14.8948	14.894	15.8711	0.9771	14.9132	0.0192	1.9650

Temp (°C)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
Single stage	1	14.5028	14.5033	16.7285	2.2252	14.5095	0.0062	0.2786
	2	14.6681	14.6683	16.3004	1.6321	14.6815	0.0132	0.8088
	3	15.4717	15.4719	17.0858	1.6139	15.4792	0.0073	0.4523
2-stage	1	14.5045	14.5037	15.0553	0.5516	14.5173	0.0136	2.4656
	2	14.667	14.6667	16.0178	1.3511	14.6945	0.0278	2.0576
	3	15.4706	15.4694	16.4991	1.0297	15.4894	0.02	1.9423

Temp (°C)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crusible after drying (g)	Weight of crusible with bio-oil (g)	Weight of bio-oil (g)	Weight after test (g)	Weight of ash (g)	Ash %
Single stage	1	14.2744	14.2744	16.1294	1.855	14.2798	0.0054	0.2911
	2	14.4946	14.4949	16.2369	1.742	14.5085	0.0136	0.7807
	3	14.8899	14.89	16.7456	1.8556	14.8977	0.0077	0.4150
2-stage	1	14.2759	14.2755	15.5129	1.2374	14.3065	0.031	2.5053
	2	14.4985	14.4988	16.193	1.6942	14.5341	0.0353	2.0836
	3	14.8949	14.8943	16.0148	1.1205	14.9169	0.0226	2.0170

SAS code for ash content of pine wood bio-char:

```
data obj3;
input temp Ash;
datalines;
1       0.326378366
1       0.771314178
1       0.435571688
1       0.27862664
1       0.808773972
1       0.452320466
1       0.291105121
1       0.780711825
1       0.414960121
2       2.440133374
```

```
2      1.80347434
2      1.964998465
2      2.46555475
2      2.05758271
2      1.942313295
2      2.50525295
2      2.08357927
2      2.016956716
;
run;
proc anova data=obj3;
class temp;
model Ash=temp;
means temp/ alpha=0.05;
run;
```

The ANOVA Procedure

Level of temp	N	Ash Mean	Ash Std Dev
1	9	0.50664026	0.21903164
2	9	2.14220510	0.25920613

Dependent Variable: Ash

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	12.03782545	12.03782545	209.06	<.0001
Error	16	0.92130141	0.05758134		
Corrected Total	17	12.95912686			

R-Square	Coeff Var	Root MSE	Ash Mean
0.928907	18.11817	0.239961	1.324423

Source	DF	Anova SS	Mean Square	F Value	Pr > F
temp	1	12.03782545	12.03782545	209.06	<.0001

Table D.4.3. Data for moisture content of pine wood bio-char (refer Table 19).

Temp (°C)	Iteration No.	Sample #1						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
Single stage	1	96.9211	100.3934	3.4723	100.2735	3.3524	0.1199	3.45
	2	93.5845	97.114	3.5295	96.969	3.3845	0.145	4.10
	3	152.4772	156.1768	3.6996	156.0545	3.5773	0.1223	3.30
2-stage	1	46.6376	49.0004	2.3628	48.9418	2.3042	0.0586	2.48
	2	46.0536	48.1655	2.1119	48.1345	2.0809	0.031	1.47
	3	46.844	49.4482	2.6042	49.403	2.559	0.0452	1.74

Temp (°C)	Iteration No.	Sample #2						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
Single stage	1	92.085	95.7132	3.6282	95.5872	3.5022	0.126	3.47
	2	113.0288	116.7161	3.6873	116.5723	3.5435	0.1438	3.90
	3	121.4935	125.0328	3.5393	124.9066	3.4131	0.1262	3.57
2-stage	1	45.8706	47.5283	1.6577	47.4859	1.6153	0.0424	2.56
	2	46.9536	49.1378	2.1842	48.8992	2.1539	0.0303	1.39
	3	43.1945	46.004	2.8095	48.6331	2.7625	0.047	1.67

Temp (°C)	Iteration No.	Sample #3						
		Weight of crucible (g)	Weight of crucible with biomass (g)	Weight of the biomass (g)	Weight of the crucible with biomass after drying (g)	Weight of the biomass after drying (g)	Weight Difference (g)	Moisture Content %
Single stage	1	96.9211	100.1032	3.1821	99.9874	3.0663	0.1158	3.64
	2	93.5845	97.2567	3.6722	97.1168	3.5323	0.1399	3.81
	3	152.4772	155.8759	3.3987	155.7569	3.2797	0.119	3.50
2-stage	1	46.6388	49.0968	2.458	49.0334	2.3946	0.0634	2.58
	2	46.0543	48.5076	2.4533	48.4745	2.4202	0.0331	1.35
	3	46.8442	49.5771	2.7329	49.5344	2.6902	0.0427	1.56

SAS code for moisture content of pine wood bio-char:

```
data obj3;
input temp moisture;
datalines;
1       3.453042652
1       4.108230628
1       3.305762785
1       3.472796428
1       3.899872535
1       3.565676829
1       3.639106251
1       3.809705354
1       3.501338747
2       2.480108346
2       1.467872532
2       1.735657784
2       2.557760753
2       1.387235601
2       1.672895533
2       2.579332791
2       1.349203114
2       1.562442826
;
run;
proc anova data=obj3;
class temp;
model moisture=temp;
means temp/ alpha=0.05;
run;
```

The ANOVA Procedure

Level of temp	N	moisture Mean	moisture Std Dev
1	9	3.63950358	0.25370939
2	9	1.86583436	0.52030408

Dependent Variable: moisture

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	14.15656117	14.15656117	84.50	<.0001
Error	16	2.68067828	0.16754239		
Corrected Total	17	16.83723945			

R-Square	Coeff Var	Root MSE	moisture Mean
0.840789	14.86991	0.409319	2.752669

Source	DF	Anova SS	Mean Square	F Value	Pr > F
temp	1	14.15656117	14.15656117	84.50	<.0001