Energy Content and Combustion Behaviour of Loose Biomass Available in Limpopo

Reuben M. Shuma, Daniel M. Madyira, Tafadzwa N. Makonese and Gert A. Oosthuizen

Abstract— Solid biomass continues to be the primary energy source for a significant proportion of Sub-Saharan African society. It is estimated that 80% of energy for heating and cooking in this subcontinent is derived from round wood biomass resulting in estimated annual rate of deforestation of 0.7%. This is unsustainable. This is despite the existence of a substantial resource of loose biomass (forest and agricultural residues) that is produced and disposed of annually. However, one major challenge in harnessing loose biomass as a source of energy is low energy density and poor combustion behaviour. Biomass briquetting technologies can be deployed to improve energy density and combustion behaviour of loose biomass. This requires understanding of the energy content in locally available loose biomass sources. This paper investigates the calorific values (energy content) and combustion behaviour of loose biomass collected from a region in the Limpopo Province of South Africa. The aim of the investigation is to understand the energy value and hence viability of using such loose biomass with the overall goal of developing recipes for biomass briquetting in the region. Calorific values were measured for 12 samples of loose biomass and their combustion behaviour analysed. Certain loose biomass sources are then identified as potential briquetting candidates.

***Index Terms*— Renewable Energy, Solid Biomass, Loose Biomass, Biomass Briquettes, Combustion, Calorific values**

1 INTRODUCTION

Biomass in the form of round wood has been used as a source of energy for many centuries. Common uses include heating and cooking especially in rural communities which do not have access to electricity. It is reported that 80% of Sub-Saharan African communities depend on round wood for energy. This is estimated to be responsible for 0.7% rate of annual deforestation. If communities continue to rely on round wood for energy, consequences include continued deforestation and global warming. Continued reliance on round wood as a source of energy is therefore unsustainable [1]. Sustainability of biomass as a source of energy can be partly achieved by harnessing loose biomass that is produced annually through agricultural and forestry activities. Common residues include maize stalks, groundnut stalks and shells, forest dry leaves, saw dust, Savannah grasses including elephant grass and others. Residues produced in perennial agricultural and forestry activities are deliberately burnt in fields or destroyed in veld fires. There is therefore significant motivation for using this loose biomass as a source of energy. The major challenge to achieving this has always been poor combustion behaviour and low energy content of loose biomass. Biomass briquetting has therefore been deployed to improve energy density and combustion behaviour. Such briquetting processes are affected by a number of factors such as moisture content and bulk density of the loose biomass that must be optimised to achieve best performance.

Tumuluru et al [2] investigated the effect of such process variables on the quality of biomass briquettes produced from wheat, oats, canola and barley. The aim was to overcome the limited application of biomass due to low bulk density. The Box-Behnken method was applied to produce briquettes in which compaction pressure is developed using a hydraulic press. Analysis of regression methods (ANOVA) were used to show that process variables such as moisture content, loose biomass density, calorific value and drying time have direct influence on the quality of the briquettes produced. However, no energy content or combustion behaviour studies were conducted either on the stock material or produced biomass briquettes.

Performance of briquetting machines was investigated by Sengar et al [3] using cashew nut shells, grass and rice husks. The aim was to find suitable methods of processing loose biomass into briquettes. A screw type press was used to produce the briquettes which were subsequently sun dried. Results indicated good performance of conversion method despite the low calorific values from grass and rice husks. Therefore, the cost benefit factor of grass and rice husks was found to be very low. This investigation highlighted the need for further research to improve quality, performance parameters and processing methods to harness energy from loose biomass.

Jorapur and Rajvanshi [4], investigated the development of a sugarcane leaf gasifier for electricity generation. The aim was to develop the use of sugarcane leaves as a source of energy without densification. Sugar cane leaves were fed into the pyrolysis unit as loose biomass demonstrating technical viability of the process. The success of this investigation was attributed to the

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small scale production process used. Upscaling of the technique could yield different results hence recommendation to conduct industry scale testing.

Bizzo et al [5] demonstrated that the residues from the bio-ethanol production process using sugarcane can be used as feedstock for biomass briquetting. The process leading to the production of trash was fully described. Although they showed lower calorific value, the trash was seen to have similar potential as bagasse as a source of energy through combustion.

Physical and combustion properties of briquettes produced from sawdust of various hardwoods (afcelia africana, terminal superba and melicia elcelsa) was investigated by Emerhi [6]. In this case various organic binders were used during the briquetting process which included starch, cow dung and wood ash. By mixing the various stock, it was possible to identify mixtures with optimum energy content. Briquettes with starch binder were found to have the highest energy content, while briquettes with ash binder had the lowest. This work demonstrated the potential and feasibility of mixing various biomass source to derive best thermal performance for the briquettes.

Pandey and Dhakal [7] used pine needles to form loose biomass briquettes and investigated their physio-chemical properties. Measured parameters included combustion behaviour which showed that pine needle briquettes had good combustion behaviour which was attributed to holes in its structure that provided large surface area. Additional work by Vassilev et al [8] and McKendry [9] also demonstrated the wide ranging behaviour of various loose biomass sources from different regions of the globe.

The use of loose biomass is not limited to small scale use. In southern China, an investigation was conducted on the potential to use giant king grass as an energy crop for direct combustion in thermal power plants and synthetic gas production [10]. This was motivated by the high energy content of the grass measured to be 18.4 MJ/kg which makes it a good candidate loose biomass material for briquetting and pelletizing. Pellets produced from this material can be fed directly into the power station furnace for steam generation.

According to Mehrabian et al [11] the combustion of solid biomass is characterised by three processes which take place in series or parallel, namely heating and drying, devolatilisation (also known as pyrolysis) and char combustion. The drying process is the first of the three processes to take place in the sequence. This process proceeds at a certain boiling temperature and is the result of the strong heating experienced on the surface of the fuel particle due to the radiation flux from the flame. This initial layer of moisture acts as heat sink and as such any additional energy beyond that required for vaporisation is further consumed for the same purpose. As a consequence of this, excessively high moisture content results in unsteady combustion.

The subsequent step in the sequence, pyrolysis, serves to decompose the dried biomass into three components i.e. char, tar and gases [12]. In the case of lignocellulosic biomass this process can be redefined as the decomposition of the three constituent pseudo components namely lignin, cellulose and hemicellulose into the three above mentioned products. According to Collazo et al [13] the volatiles are composed mainly of CO, CO_2, H_2, H_2O, NH_3, light hydrocarbons (represented by CH_4) and tars (usually represented by C_6H_6). The proportions of the components of the volatile mixture are determined by the temperatures. The oxidation of these volatiles takes place homogeneously in the gas region of the combustor set up (freeboard).

Finally, according to Turns [14] char consists mainly of carbon (C). In char combustion the flame front is found to be removed from the char surface in addition to being diffusion driven. In this case the char surface is attacked by CO_2 and the resultant CO diffuses away from the fuel particle surface and towards the flame front from one direction while O_2 diffuses towards the flame front from the opposite direction in stoichiometric proportions to produce CO_2. This reaction is assumed to be taking place at an infinite rate and as such both the concentrations of CO and O_2 are zero at the flame front where the temperature is at a peak. The energy derived from the combustion process is known as the heat of reaction which is representative of the net change in energy between the reactants and the products as captured by equation (1).

$$\sum_{i\,product} n_i\left(\overline{h^{\circ}_{f,i}}(T_{ref}) + \Delta\overline{h_{s,i}}(T_i)\right) - \sum_{j\,reactant} n_j\left(\overline{h^{\circ}_{f,j}}(T_{ref}) + \Delta\overline{h_{s,j}}(T_j)\right) = \Delta H \qquad (1)$$

where n_i, $\overline{h^{\circ}_f}$, T_{ref}, $\Delta\overline{h_s}$, T_i, T_j, n_j and ΔH respectively refer to number of moles of the i^{th} product, molar standardised enthalpy of formation, reference temperature, sensible enthalpy change in going from T_{ref} to T, i^{th} product temperature, j^{th} reactant temperature, number of moles of the j^{th} reactant and the heat of reaction. In the instance that all the heat derived from the combustion process is used to heat the products ($\Delta H = 0$), the product temperature is referred to as the adiabatic flame temperature.

Additionally, combustion temperatures are dependent on the proportions of the fuel and oxidizer in the reaction mixture [14]. These proportions are frequently measured through the aid of a parameter known as the equivalence ratio. This is a ratio of the stoichiometric air to fuel ratio to the actual air to fuel ratio. If this value is unity the mixture proportions are stoichiometric. However, if this value is greater than unity the mixture is termed fuel rich and alternatively termed fuel lean in cases when this value is less than unity. The maximum flame temperature is obtained when stoichiometric reactions occur.

It is clear from literature that the process of producing a good quality briquette directly depends on a number of factors such as the nature of the material, moisture content, loose and compacted density, energy content and combustion behavior. These factors must be optimized to improve utilization of loose biomass as a source of energy. Although the energy from biomass is extracted mainly by combustion, biomass can also be used to produce bio-gas and synthetic gas through pyrolysis. This expands application to internal combustion engines and larger power plants. In light of these benefits and more, it is essential to investigate the materials that can be used to produce good quality briquettes. The purpose of this paper is to investigate the energy content and combustion behavior of loose biomass available in a particular location in Northern South Africa with the ultimate goal of identifying loose biomass that is most suitable for loose biomass briquette production in the region.

2 EXPERIMENTAL PROGRAMME

2.1 Aim of the Investigation

The aim of this investigation is to determine the energy content and combustion behaviour of loose biomass freely available in a region of northern South Africa.

2.2 Materials

Twelve different types of loose biomass were collected from freely available forest and agricultural residues. These included maize cobs, maize stalks, maize leaves, grass (yellow thatching grass), ground nut stems, ground nut leaves, ground nut shells, wall nut shells, coconut shells, cow dung, sugar cane leaves, blue gum saw dust and Mopani leaves and bark. These materials were collected from Maphophe Village (Vhembe District) and Vuwani village (Levhubu District) located in the Northern Limpopo Province of South Africa.

2.3 Sample Preparation

2.3.1 Calorific Value

For calorific value measurement, loose biomass samples were cut into very fine pieces for loading into testing crucible. The prepared material was then weighed into 0.5 g sample sizes for testing.

2.3.2 Combustion

Loose biomass samples were prepared into approximately 100 mm long particles. Unprocessed loose samples were used for moisture content measurement. All moisture content samples were measured into 30 gram batches and placed on an aluminum foil tray. The aluminum foil trays are marked with numbers to identify each sample. After moisture content testing, the loose biomass samples were then cut into approximately 200 mm long pieces. Samples are placed inside a steel tray then measured to 200 grams per each type for combustion performance tests.

2.4 Description of Equipment

2.4.1 Calorific Value Measurement

A bomb calorimeter (CAL2K) with power rating of 50/60 Hz and 90 - 260 VAC was used for calorific value measurements. It had a temperature resolution of 0.000001 °C with operating temperature range of 0 - 60°C. The repeatability of the equipment is specified as 0.1° (%RSD - Relative Standard Deviation) with a resolution of 0.001 (MJ/Kg). CAL2K system (Fig. 1) consists of three main components which are oxygen cylinder with a high pressure oxygen regulator operating with supply pressure up to 3 MPa, the oxygen filling station, the combustion chamber which has intelligent (SMART) vessel with built-in microprocessor at the base that enables firing counts, sample identification, memory for tested samples and reconditioning of data, the cooler which cools down recently fired testing chamber to normal ambient temperature within 3 to 4 minutes and the computer system for data logging and analysis. An Adventurer Analytical Balance laboratory scale model AR0640 was used for weighing the samples. The scale has a capacity of 65 grams, with various weighing modes that permit measuring in milligrams and grams with a repeatability (standard deviation in milligrams) of 0.1.

Figure. 1: CAL2K ECO Bomb Calorimeter

2.4.2 Combustion Monitoring

Imbawula Entsha combustion stove with internal ceramic lining and a built-in air flow nozzle was used for combustion tests (Fig. 2(a)). It has a removable cap which allows for airflow control. During combustion testing, the stove was placed on an CBW-15 Adam scale to monitor the combustion rate. The scale has a capacity of 15 kg. A fume hood was placed above the stove to collect exhaust gases and particles. It was equipped with emissions sampling pipes (Fig. 2(b)) with dilutor and in-line air filters. K type thermocouples were used to monitor exhaust gas temperatures. They have temperature measurement ranges of 0 to +1100^{o}C for continuous measurements and -180 to +1350^{o}C for short term measurements. Gases collected from the hood were fed to a TSI Dust Trak 8530 for emissions particle size analysis. It has capacity to measure PM10, PM 2.5 and PM 1.0 particle sizes. Two Abgas analysers (Testo 35-s) were used for measuring diluted and undiluted particle emissions linked to a computer for data logging (Fig. 2(c)).

(a) (b) (c)

Figure. 2: (a) Imbawula Entsha under hood (b) Emissions extraction (c) Gas analysers

2.5 Testing Procedure

2.5.1 Energy Content

The CAL2K-ECO bomb calorimeter was calibrated using benzoic acid tablet to the mass of approximately 0.5 grams and measured using Adventurer DHAUS scale to confirm the mass. Weighed samples of various loose biomass were then tested. Each sample must be confirm to be 0.5 grams. Each test sample is placed inside the crucible which is then placed on top of the scale pan with the crucible weight compensated. Thee sample is then transferred to the vessel which is charged with oxygen to a pressure of 3 MPa. The vessel is then loaded into the bomb calorimeter and the testing initiated. Cotton firing thread was used for all tests.

2.5.2 Combustion Behaviour

Moisture content

Before combustion testing, the moisture content of each type of loose biomass was determined. A 31 grams sample was weighed and placed in an oven set at 100^{o}C. Sample were weighed at 1 hour interval until constant mass was achieved. The moisture content is then reported as a fraction of the change in mass to dry mass.

Combustion characteristics

For combustions tests, 200 grams samples of loose biomass were placed in Imbawula Entsha stove. The stove was placed on a scale as shown in Figure 2 (a) and (b). Changes in mass was then sampled through a desktop computer. Matches was used to ignite the samples. For sample with poor combustion, paraffin was used to encourage ignition. The combustion time was recorded while monitoring the burning rate. Temperatures were recorded using a National Instruments DAQ SCXI-1000 equipment using Signal Express software.

3 RESULTS

3.1 Energy Content

The energy content of loose biomass was measured using the bomb calorimeter. The calorific values of the various loose biomass type collected from the Limpopo Province of South Africa are shown in Table I. They represent the most commonly available loose biomass in the area that have potential as briquetting stock. From Table I it is clear that ground nut shells have the highest amount of specific energy followed by eucalyptus saw dust. This is surprising as saw dust is expected to yield the highest density since it's derived from round wood. Cow dung has the lowest energy content. The poor energy content of cow dung could be due to elevated moisture content. Cow dung is a commonly used fuel source in most communities that are not connected to the electricity supply grid and have limited round wood resources. In addition cow dung has also been used as a binder for briquetting purposes. Of the naturally available forest residues, Mopani leaves have the highest energy content followed by yellow thatching grass.

Table I: Calorific values of loose biomass sample collected from Limpopo

BIOMASS PRODUCTS	CV (MJ/kg)
Sugar Cane Leaves	16.38
Mopani Bark	16.37
Mopani Leaves	18.81
Ground Nut Shell	20.31
Ground Nut Leaves and Stem	17.23
Yellow Thatching Grass	16.73
Coconut Shell	18.31
Eucalyptus Saw Dust	19.97
Cow Dung	12.87
Maize Cobs	17.5
Maize Leaves	15.58
Maize Stalk	14.62
Coconut Skin	16.55
Walnut Shells	18.58
Sweet Sorghum Seeds	16.00

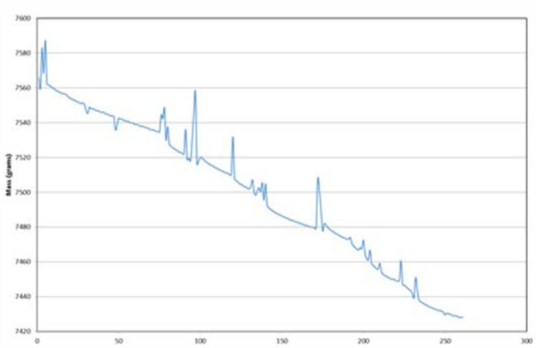
3.2 Combustion Performance

Density and moisture content was measured for each type of loose biomass prior to combustion testing. The results of density and moisture content tests are given in Table II. As expected Eucalyptus saw dust has the highest density while maize cobs have the lowest density. Sugarcane leaves recorded the highest moisture content followed by cow dung, maize cobs and coconut shells. Groundnut leaves, stem and leaves recorded the lowest moisture content. This could have been responsible for the highest specific energy content reported in Table I.

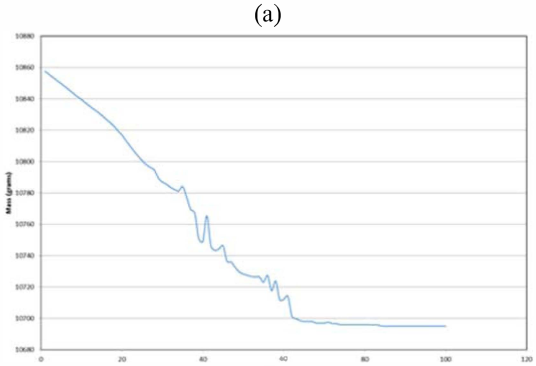
Table II: Combustion performance data for selected loose biomass

BIOMASS PRODUCT	DENSITY (kg/m³)	MOISTURE CONTENT (%)	TIME (sec)	RATE (g/sec)
Sugar Cane leaves	0.017	19.2	89	2.44
Mopani Barks	0.055	14.8	72	2.71
Mopani Leaves	0.045	10.7	72	2.71
Ground Nut Shell	0.018	3.3		
Ground Nut Leaves and Stem	0.062	3.3	84	3.3
Yellow Thatching Grass	0.023	2.0	129	1.51
Coconut Shell & Skin	0.075	10.7	126	2.43
Eucalyptus Saw Dust	0.977	6.9	254	0.54
Cow Dung	0.038	10.7	316	0.59
Maize Cob	0.14	10.7	112	3.19
Maize Leaves	0.015	6.9	105	0.71
Maize Stalk	0.2	6.9	93	2.8

Typical variation of mass with time during combustion for the selected loose biomass is shown in Fig. 3. Each sample started with a mass of 200 grams. Certain materials such as saw dust required controlled feeding of the material to maintain consistent combustion hence the peaks in the graphs. All graphs show consistent mass decay with cow dung displaying the most smooth burn rate.



(a)



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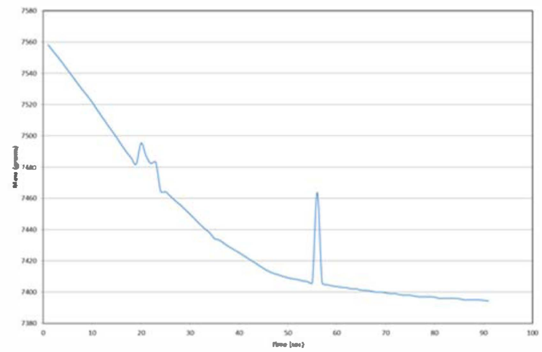

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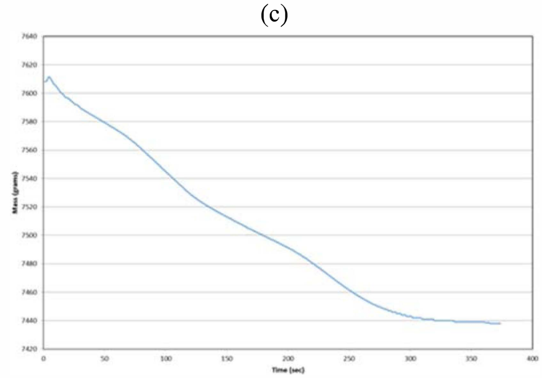

(d)

Figure. 3: Combustion performance (a) Eucalyptus saw dust (b) Mopane leaves (c) ground nut stem and leaves (d) cow dung

A comparison of all the loose biomass tested is shown in Fig. 4. The burn rate is computed by taking the slope of the combustion curve for any given sample.

4 DISCUSSION

4.1 Calorific Value Content

Calorific values in MJ/kg were measured for 12 loose biomass samples collected from Limpopo Province of South Africa. Five samples displayed high levels of energy content. These samples are ground nut shells, eucalyptus saw dust, Mopani leaves, coconut shell, ground nut stem & leaves and maize cobs. Cow dung has the lowest energy content but is a good briquette binder. Of available agricultural and forest residues ground nut shells and Mopani leaves are therefore good candidates of biomass briquetting based on energy content.

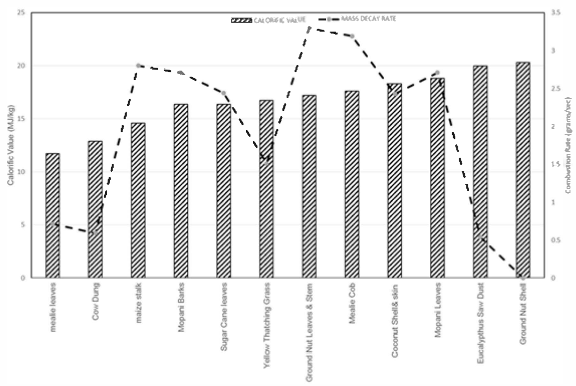

Figure. 4: Comparison of Calorific Value and Burn Rate for Selected Loose Biomass

4.2 Moisture Content

The amount of moisture in a material to be determines the amount of energy that can be usefully extracted. Higher moisture content implies higher energy expended in evaporating the moisture thus reducing useful energy. Moisture content of all measured loose biomass indicate that sugar cane leaves have the highest content followed by Mopani barks. The amount of moisture content indicate the significant drop in maize cobs, coconut shell & skin and cow dung. Mopani leaves and yellow thatching grass have the lowest moisture content. Therefore yellow thatching grass becomes a potential briquetting candidate material. However, solar drying technologies developed by the authors can be deployed to reduce moisture especially after briquetting to ensure maximum energy value.

4.3 Density

Eucalyptus saw dust has the highest density. This is expected at it is extracted from round wood. This is followed by maize stalk, maize cobs, coconut shells, ground nut leaves & stems and Mopani bark. Sugar cane leaves have the lowest density despite its high energy content. Based on density, eucalyptus seems to have the highest potential. However material of the lowest density and high energy content are also good candidates.

4.4 Burn Rate

Combustion patterns were observed to be similar for almost all samples. Results show that cow dung burns longest with a burning rate of 0.59 grams per second. However high emissions were observed through a lot of initial smoke. The low burn rate might be responsible for the widespread use of cow dung for cooking and heating as sustained fires are required. Eucalyptus saw dust also has a low burning rate at 0.54 grams per second. Mopani barks and leaves had the lowest combustion time and highest burning rate at 2.71 grams per second. Based on burn rate, the most attractive material is cow dung followed by eucalyptus saw dust. Maize leaves and yellow thatching grass all exhibit favourable combustion behaviour.

5 CONCLUSIONS

Experimental investigation of energy content and combustion on loose biomass was conducted on twelve samples of loose biomass collected from the Limpopo Province of South Africa. These were the most widely available loose biomass in the region. Performance of the selected loose biomass was characterised based on energy content, density, moisture content and burning rate. The results give an indication of potential candidate materials for briquetting in that region. However, the final choice of briquetting materials is influenced by various factors which include availability of materials, briquetting process chosen, energy content, moisture content, and combustion behaviour. Eucalyptus saw dust and peanut shells have the highest energy content which make them good candidates for briquetting. However, considering other factors, the materials of choice are maize stalk, maize cobs, ground nut leaves & stalk and cow dung. Cow dung is particularly selected for its binding properties.

6 RECOMMENDATIONS

Further work will be required to produce the biomass briquettes using the selected stock materials and test their behavior to validate performance. In addition, health impact assessment from emissions and the characterization of the gases emitted by all potential loose biomass materials must be investigated to ensure that they are safe to use.

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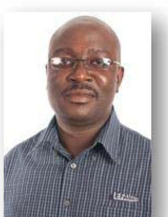

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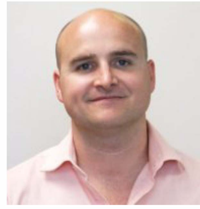

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