Characterization and Heating value Prediction of Municipal solid waste

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Abstract— *There is an increasing trend of using municipal solid waste as an alternative energy resource, burning and converting it into energy in the form of heat or steam or electricity. The aim of this study is to predict energy value of MSW using compositional and proximate-based analysis of solid waste and compare the reliability of models in predicting the energy recovery potentials from different solid waste components. Physical characterization showed that food, yard, textile, leather, rubber, wood scrap, yard, metal, plastic and paper waste were the constituents of all waste samples in the study area, but in varying proportions. The energy content of combustible solid waste was estimated to be 17.50 MJ/kg for gross heating value, and 9.54 MJ/kg for net heating value, which revealed the suitability of solid waste as energy recovery option. In this study several proposed composition and proximate-based mathematical models have been used to estimate the HHV of municipal solid waste. The average high heating values estimated from some models were found to be 16.27 ± 0.90 MJ/kg (Model II), 16.45 ± 0.43 MJ/kg (Model III), 18.97 ± 0.03 MJ/kg (Model XVIII), and 16.60 ± 0.32 MJ/kg (Model XXIV) which were closely match the value with experimentally determined calorific value as 17.50 ± 0.68 MJ/kg. Therefore, it is concluded that the quantity of energy obtainable from a known amount and composition of mixed solid waste can be estimated using already developed models without conducting calorimetric experiments.*

Keywords— ***Characterization, Heating value; Models, Proximate Analysis, Municipal solid waste.***

I. INTRODUCTION

Municipal solid wastes, collected from cities, have recently thought as one of the important renewable energy resources. Recovering energy by means of a number of energy generation processes such as combustion, pyrolysis and gasification from municipal solid waste is feasible [1]. This method will reduce the quantity of incoming solid waste to dumping site and also open opportunities for new technologies in treating MSW. The first step to understand the feasibility of design energy conversion (incineration plan) is to obtain the basic data regarding to quantity and quality of generated MSW [2].

This research study was primarily motivated by the lack of laboratory facilities in calorific value and ultimate analysis in Ethiopia and this article is a continuation of Fetene et al., [3] and aims to determine the reliability of models in predicting the energy recovery potentials from different solid waste components at Jimma city households. Researchers have developed many empirical models. The mathematic models for the evaluation of heating value from physical and chemical properties have been developed by several researchers, and have reviewed several of these models based on physical composition and proximate and ultimate analysis [4]–[9]. However, given the determination of ultimate analysis data is relatively expensive, therefore, for the practice purpose correlation based on proximate analysis data will be more profitable. This data is the easiest and most widely used in the characterization of fuels mainly solid fuel.

II. MATERIALS AND METHODS

2.1 Sampling Protocol and waste characteristics

Each of the 6 districts/kebeles was sampled at random three times a year in all seasons namely: dry (March), rainy (July), and in between the two seasons (November) [10], [11]. The waste from the assigned households was collected onto a clean, impervious floor where it was mixed rapidly with a shovel and quartered. Finally, components of solid wastes were sorted, weighed and recorded based on the standard procedure [10], [11]. Homogenized samples with appropriate sampling, handling and transportation mechanism were taken to laboratory for proximate analysis and calorific value determination.

2.2 Proximate analysis

The proximate analysis, gives percent of moisture content, ash content, volatile matter and fixed carbon, were determined by putting the samples to different range of temperature (100°C to 950°C). The laboratory methods to measuring the proximate analysis of samples in this study were conducted according to ASTM standards described in [10], [12] [13], [14].

2.2.1 Moisture content (ASTM D 3173)

The sample will be dried in an oven at 105°C for one hour to a constant weight. The percent MC was calculated as a percentage loss in weight before and after drying for each solid waste component.

2.2.2 Ash Contents (ASTM D 3174)

The ash content was determined by drying the samples and burning at 750°C for 1 hour in a furnace.

2.2.3 Volatile matter (ASTM D 3175)

The dried sample will be heated at 950°C for seven minute in muffle furnace. After combustion, the samples were weighed to determine the ash dry weight, with volatile solids being the difference between the dried solids and the ash

2.2.4 Fixed Carbon

The carbon content in the ash sample was determined by removing the mass of volatile from the original mass of the sample using the following equation:

$$\mathrm{FC} = 100 - (\%\mathrm{MC} + \%\mathrm{AC} + \%\mathrm{VS})$$

Where: MC is moisture content, AC is Ash content, VS is Volatile matter

2.3 Prediction of Energy content (calorific value)

Calorific value of solid waste usually described in terms of high heat value (HHV) and lower heat value (LHV), which can be determined either experimentally using Bomb calorimeter or by using mathematical models [15]. The calorific value, expressed as kcal/kg or KJ/Kg, Experimentally energy value is determined using Bomb calorimeter (ASTM D 5865-85) in which the heat generated at a constant temperature of 25^{o}C from the combustion of a dry sample is measured [16] [17], [18].

In case when direct calorific value measurements are not feasible, empirical models can be useful to predict the calorific value of municipal solid waste (MSW) [23]. Several models have been developed to describe and predict the energy content of commingled MSW. The common independent variables in such empirical models are either the elemental composition [23], the physical composition [24] or the proximate composition (i.e., the content in volatile matter, moisture, fixed carbon) of MSW [20]. Some of the models that correlate the energy content of MSW with its composition and proximate analysis used in study presented in Table 1 & 2.

TABLE 1
MODELS SELECTED FROM LITERATURE REVIEW FOR THE PREDICTION OF HEATING VALUE BASED ON SOLID WASTE COMPOSITIONAL ANALYSIS

Models	Models Equation	Basis	Units	References
Model I	$LHV = (23(P_{Fo} + 3.6P_{Pa}) + 160(P_{Pt} + P_{Ru})) \times 2.326$	Wet	kJ/kg	[19]
Model II	$HHV = 112.15P_{Fo} + 183.386P_{Pa} + 288.737P_{Pt} + 5064.701$	Wet	kJ/kg	[20]
Model III	$HHV = 81.209P_{Fo} + 285.035P_{Pa} + 8724.209$	Wet	kJ/kg	[21]
Model IV	$HHV = 112.15P_{Fo} + 184.366P_{Pa} + 298.343P_{pt} - 1.920M + 5130.380$	Wet	kJ/kg	[21]
Model V	$LHV = 6.0P_{Fo} + 22.1P_{pa} + 28.1P_{Pt} + 12.7P_{Wo} + 24.6P_{Te} + 57.4P_{Ru} + 17.2P_{Mi}$	Wet	Kcal/kg	[22]
Model VI	$LHV = (45.2P_{Fo} + 47.3P_{Pa} + 58.6P_{Pt} + 32.4P_{Wo} + 38.6P_{Te} + 62.3P_{Ru} + 50.1P_{Mi})(100-M)/100-6M$	Dry	Kcal/kg	[22]
Model VII	$LHV = (42.21T_{Ga} + 35.19P_{Pa} + 71.17P_{Pt} + 48.06P_{Wo} + 36.24P_{Te} + 44P_{Mi})(100-M)/100-6M$	Dry	Kcal/kg	[22]
Model VIII	$LHV = 2229.91 + 4.87T_{Ga} + 7.9P_{Pa} – 37.28M$	Dry	Kcal/kg	[23]
Model IX	$HHV = 267.0(P_{Pt}/P_{Pa}) + 2285.7$	Dry	Kcal/kg	[24]
Model X	$HHV = [88.2P_{Pt} + 40.5(P_{Fo} + P_{Pa})] (100-W)/100 – 6W$	Dry	Kcal/kg	[24]
Model XI	$HHV = [(100 – W)/100][38.8(P_{Pa} + P_{Fo} + P_T + P_{Oc}) + 50.9(P_{Te} + P_{Ru}) + 73.7P_{Pt}] – 6W$	Dry	Kcal/kg	[20]
	P_{Fo}: food waste (wt%); P_{Pa}: paper and cardboard (wt%); P_{Pt}: plastics or plastics and rubber (wt%); P_{Ru}: rubber (wt%); M: moisture (wt%); P_{Wo}: wood waste (wt%); P_{Te}: textile (wt%); P_{Mi}: miscellaneous components (wt%); T_{Ga} : garbage (wt%; textiles, wood, food waste, miscellaneous also included); W: water (wt%); P_T: wood and glass (wt%); P_{Oc}: other combustibles (wt%).			

TABLE 2
MODELS SELECTED FROM LITERATURE REVIEW FOR THE PREDICTION OF HEATING VALUE BASED ON SOLID WASTE PROXIMATE ANALYSIS:

Models	Models Equation	Basis	Units	References
XII	HHV = -0.125M + 17.251	Dry (Wt %)	MJ/kg	[12]
XIII	HHV = 19.44 - 0.258A	Dry (Wt %)	MJ/kg	[12]
XIV	HHV = 2.467 + 0.196VM	Dry (Wt %)	MJ/kg	[12]
XV	HHV = 9.355 + 0.38FC	Dry (Wt %)	MJ/kg	[12]
XVI	HHV = -9.509 +0.259(VM+FC)	Dry (Wt %)	MJ/kg	[12]
XVII	HHV = -30.727 + 0.459VM + 0.716FC	Dry (Wt %)	MJ/kg	[12]
XVIII	HHV = 0.192A + 0.459VM + 0.716FC - 30.727	Dry (Wt %)	MJ/kg	[12]
XIX	HHV = 0.185A + 0.467VM + 0.712FC + 0.056M - 31.723	Dry (Wt %)	MJ/kg	[12]
XX	HHV = 0.226A + 0.519(VM+ FC) -31.916	Dry (Wt %)	MJ/kg	[12]
XXI	HHV = -10.81408 + 0.3133(VM + FC)	Dry (Wt %)	MJ/kg	[21]
XXII	HHV = 19.914 - 0.2324A	Dry (Wt %)	MJ/kg	[8]
XXIII	HHV = -3.0368 + 0.2218VM + 0.2601FC	Dry (Wt %)	MJ/kg	[8]
XXIV	HHV = 0.196FC + 14.119	Dry (Wt %)	MJ/kg	[6]
XXV	HHV = 0.312FC + 0.1534VM	Dry (Wt %)	MJ/kg	[25]
XXVI	HHV = 0.3543FC + 0.1708VM	Dry (Wt %)	MJ/kg	[26]
XXVII	HHV = 356.248VM - 6998.497	Dry (Wt %)	KJ/Kg	[20]
XXVIII	HHV = 356.047VM - 118.035FC - 5600.613	Dry (Wt %)	KJ/Kg	[20]
XXIX	HHV = 44.75VM - 5.85W + 21.2	Wet (Wt %)	Kcal/Kg	[20]

III. RESULTS AND DISCUSSION

3.1 Waste characterization Studies

The composition of household solid waste are not homogeneous, it vary according to changes in commercial activities, population behaviour, consumption patterns and economic growth rates. Food waste that include food left over, egg shells, fruit or vegetable peels, cooked food, and food preparation wastes from residences comprise the largest component of Jimma town HHs MSW stream which accounts 35.14%. Yard waste comprises the second largest components of Jimma town MSW stream (23.65%), which includes grass clippings, leaves, and tree trimmings. Paper and paper products comprise 17.08% of Jimma household MSW stream. This result is in agreement with those results obtained for Ethiopian cities Diriba [27] in

Hawassa town, Cheru [28] in Dessie town where the food and yard waste were found to be the major component of the solid waste stream generated. The products that comprise paper and paperboard wastes are newspapers, magazines, office papers, tissue paper, cigarette packages and towels, paper plates and cups, corrugated boxes, milk cartons. Plastic products comprise 14.3% of the total MSW in Jimma town. Plastic products were found in nondurable goods (plastic plates and cups, trash bags, disposable diapers), and plastic containers and packaging (soft drink bottles, bags, sacks, wraps). The plastic products are consisting mainly of plastic food items, trash bags, milk and water bottles, and soft drink bottles.

Metals comprising 0.07% of the total MSW consists mainly of aluminium (foil), ferrous metals (iron and steel found in appliances, furniture, and corroded metal scrap, containers and packaging materials), and non-ferrous metals (copper, zinc, and lead found in durable products such as appliances and consumer electronics). Glass and ceramics products comprise 0.40% of the total MSW and occurred primarily in the form of containers as soft drink bottles, bottles and jars of food, and other consumer products. Textile (occurred in discarded clothing, footwear) and rubber and leather products (occurred in bicycle tires, Leather (clothing and shoes) were found in Jimma MSW stream in small amount (1.07% and 1.46% respectively). Some hazardous materials (insignificant amount) were also recognized in Household MSW stream of Jimma town such as paint strippers, batteries and paint residues. Accordingly, about 33.31% of total wastes generated have a potential for recycling and consisting of paper products (17.08%), plastic waste (14.3%), wood scrap waste (1.46%), metals waste (0.07%), and glass and ceramics waste (0.4%). Knowing that not whole portion of paper, plastic, wood scrap, metals and glass and ceramics waste are applicable for recycling; a separate study should be conducted to separate all materials into recyclable and non-recyclable portion. In general, household solid waste in Jimma city is characterized by a high organic content and combustible matter consisting of food, yard, textile, paper, and plastic comprising 91.24% of the total waste suggesting that energy and plant nutrients can be recovered.

As Figure 2 shows, the result from quantity of yard waste wasn't consistent during the sampling period and fluctuated from 21.05 to 26.31%. Another main component was the paper and paper which made about 17.08% and 14.3% of the total weight. According to the result from sorting process, the amount of mixed paper, wood, Rubber & Leather, glass & ceramics and metals that comes from residential weren't much different during the sampling period, with an average 17.08%, 0.52%, 1.46%, 0.40%, and 0.07% of total waste per day respectively (Fig. 1).

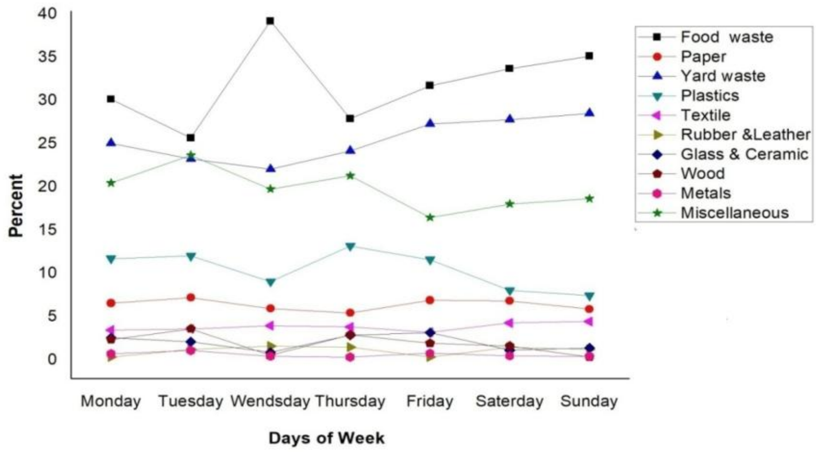

FIGURE 1: Variation of waste categories quantity within a week

3.2 Chemical Waste composition Analysis

Another important parameters used for prediction of MSW heating value is proximate analysis basically it helps in deciding and setting up a good waste processing and disposal facility in the city and in determination of efficiency of a waste treatment process [29]. Proximate analysis involves determination of moisture content, volatile matter, ash content and fixed carbon of sample. The analysis was performed according to ASTM method. In [3] were reported that MSM in Jimma city, containing an average of 63.38% volatile matter, 3.13% ash, and 4.08% fixed carbon in dry basis, and the average moisture content is 39.60%. High moisture content of solid waste has negative and undesirable effect on applicability of the waste for energy recovery as it adds weight to the fuel without adding to the heating value. Result from moisture content analysis directly affected by the quantity of wet basis materials such as yard waste and food waste in waste stream. Higher percentage of yard waste (28.17%) and food waste (34.79%) on Sunday compare with result on Tuesday (yard waste 22.92 % and food waste 25.33%) is the reason of increasing the percentage of moisture content.

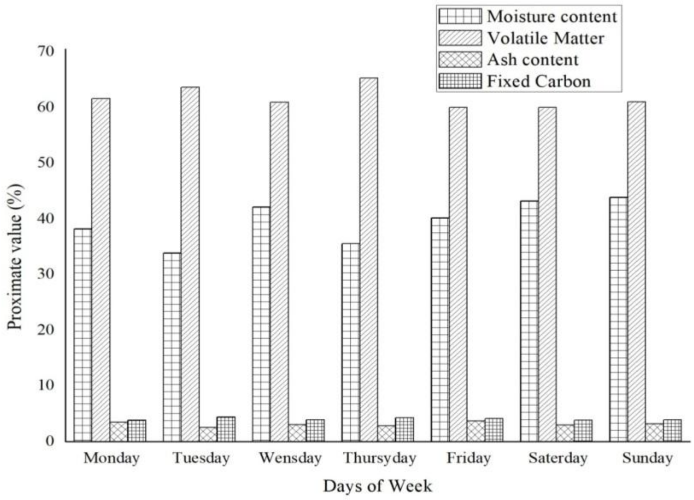

FIGURE 2: Obtained results from proximate analysis of composite household solid waste

The inorganic components including miscellaneous present in the sample (stones, metals, glass, etc.) were removed from laboratory analysis after sorting. Therefore, only the selected organic & combustible fraction of the households MSW was analysed. Based on the above, the results of the analyses of the household MSW are expressed on a per organic fraction basis; that is, the results are expressed per MSW fraction after the removal of the inorganic components (stones, glass, metals), since no calorific value analyses were performed on the inorganic fraction. To express calorific value per total commingled MSW, then the values reported here should be multiplied by [1- inorganic fraction of the commingled MSW]. The inorganic fraction of the commingled MSW used in this research work ranged from 0.16 to 0.23.

3.3 Heating value (Calorific value)

3.3.1 Experimental Result using Bomb calorimeter

Calorific value is the amount of heat generated from combustion of a unit weight of a substance, expressed as kcal/kg (KJ/Kg). The calorific value is determined experimentally using Bomb calorimeter in which the heat generated at a constant temperature of 25˚C from the combustion of a dry sample is measured. Since the test temperature is below the boiling point of water, the combustion water remains in the liquid state. However, during combustion the temperature of the combustion gases remains above 100˚C so that the water resulting from combustion is in the vapor state shows typical values of the residue. The experimental result indicated that the energy content of the Jimma city HHs solid waste was vary from 16.35 to 17.98MJ/kg (Fig. 3) with the average value of 17.5 MJ/kg as dry basis and 9.54 MJ/kg for net heating value which fit the minimum level value required for incineration projects [3]. The acceptable recommended energy recovery range from solid waste suggested by Whiting is 7.50 MJ/kg to 12 MJ/kg [30]. The heating value of composite (mixed) HHs solid waste (9.54 – 17.5 MJ/kg) was approximately about one-half of the calorific value of coal (25 – 30 MJ/kg) and one-third of fuel oil (45 MJ/kg) and Natural gas (54.75 MJ/kg) [3].

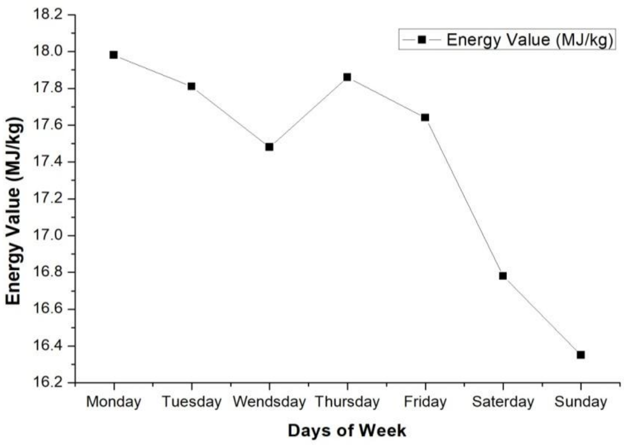

FIGURE 3: HHV values (MJ/Kg) determined from laboratory analysis

3.3.2 Energy values determined using mathematical models

The elemental composition of MSW can significantly vary among countries, regions and cities, as a result of differences of the physical composition of MSW [3], [31]–[33]. The physical composition of MSW is usually dependent on the socio-economic conditions of a country, its population size, the climatic conditions and the national environmental legislation [24]. The knowledge of the calorific value of MSW is necessary to design MSW incinerators for energy recovery purposes [23], [34]. In case of laboratory calorific value measurements are not feasible, empirical models can be used to predict the calorific value of municipal solid waste [23]. For this study some models have been used to predict the calorific value of mixed solid waste [20], [24].

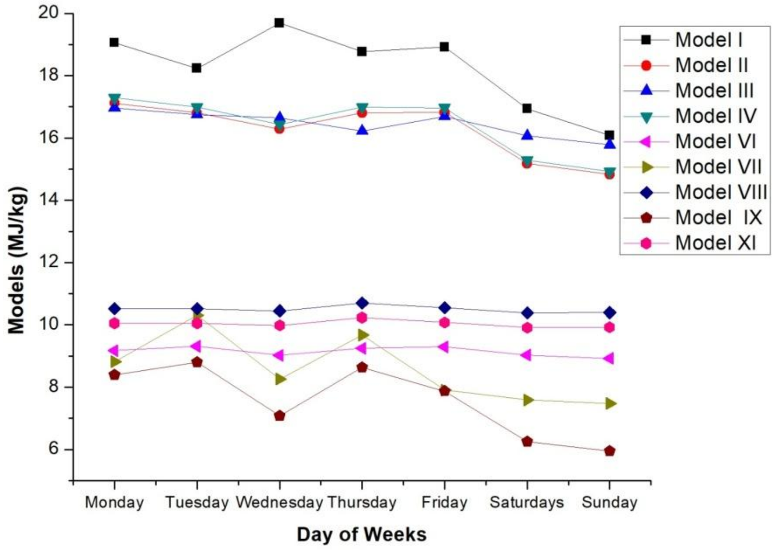

FIGURE 4: HHV values (MJ/Kg) from model based on Composition analysis.

According to thus models (model I-XI) plastics waste (Pl) appears to be the dominant predictor of calorific value. Yard and paper waste do not appear in all of the models, whilst food waste are almost always present, except from some models (model VII, VIII & IX) in which food waste is absent (Table 1). Models (XII - XXIX) are empirical formulas that are based on the proximate analysis of MSW (Table 2) which includes the weight of the organic matter (i.e., volatile matter) as the main predictor, fixed carbon and moisture contents of calorific value. The advantage of using proximate analysis data were that it gave result based on sample sizes where about models [23]. The positive point is that, these models do give an accurate estimation of the calorific values of the samples.

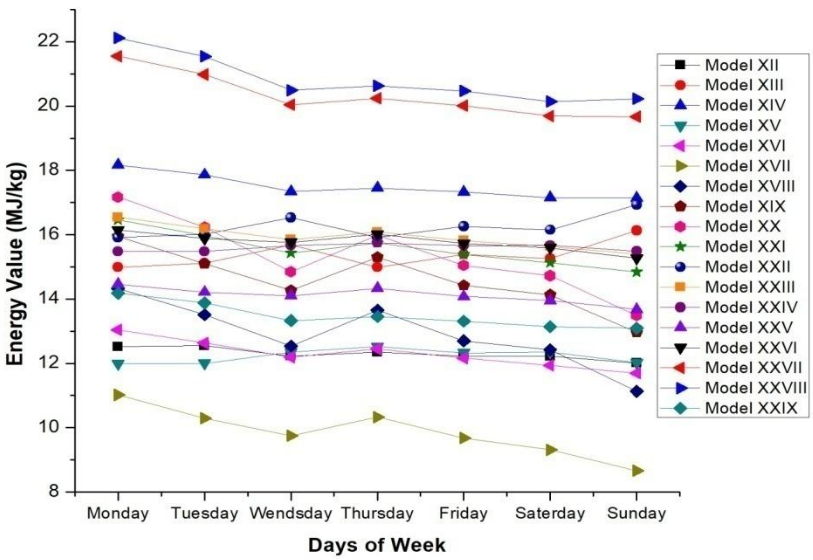

FIGURE 5: HHV values (MJ/kg) from model based on proximate analysis

Based on composition and proximate analysis the predicted HHV values as compare to selected different days of sampling period, Food, plastic and paper waste are the examples of components which contribute positively towards the calorific value. Plastic as an individual component accounted for about 14.3% of the total daily disposal MSW and contribute the most of the heating value (40,809.7KJ/kg) followed by paper (16,192.62 KJ/kg) and yard waste (16,411.88 KJ/kg). Increasing the amount of plastic in waste stream on Thursday compare to Wednesday was a reason on obtained the higher volatile matter and higher value of HHV in that day. As figure 5 & 6 showed that there were small difference between the results from model II (R^2 = 0.667), model III (R^2 = 0.768), model IV (R^2 = 0.667), model XIV (R^2 = 0.823), model XVI (R^2 = 0.877), model XVII (R^2 = 0.837) and model XX (R^2 = 0.789) gave the almost good prediction of HHV values as compare to others model (Fig. 5-8). Thus, model XIV, model XVI, model XVII and model XX were the best model in this category compared to the actual HHV laboratory result (17.5 M /Kg). The finding of compositional and proximate analysis results strengthens the argument that models are best suited in their own area and this finding precise and accurate in predicting the HHV of MSW in Jimma city.

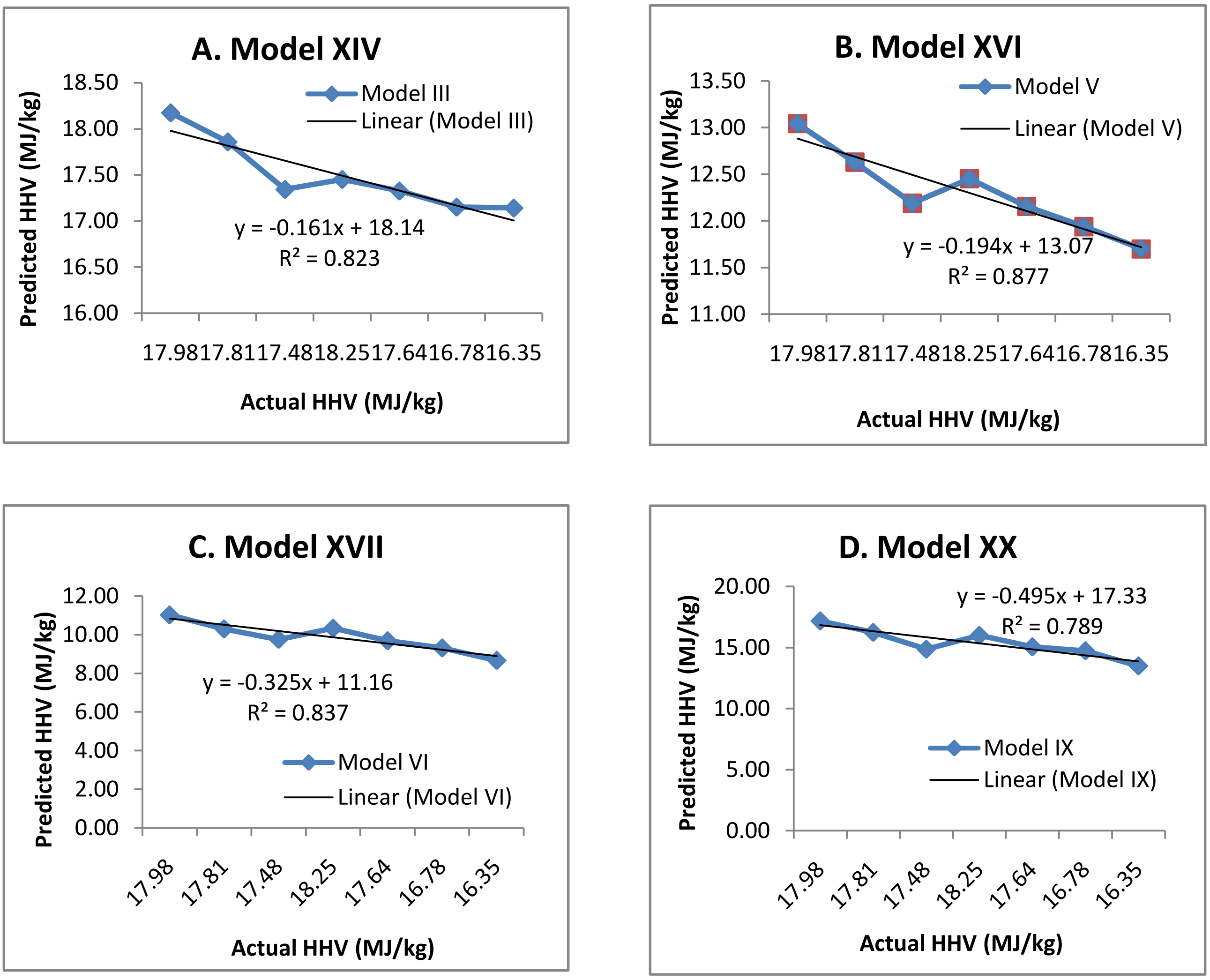

FIGURE 6: R^2 values of selected models from proximate based analysis

The linear analysis confirmed that the assumption of a linear relationship was valid, and as expected, the model indicates that plastics, paper, and organic contribute positively to the energy content, while water is negatively correlated.

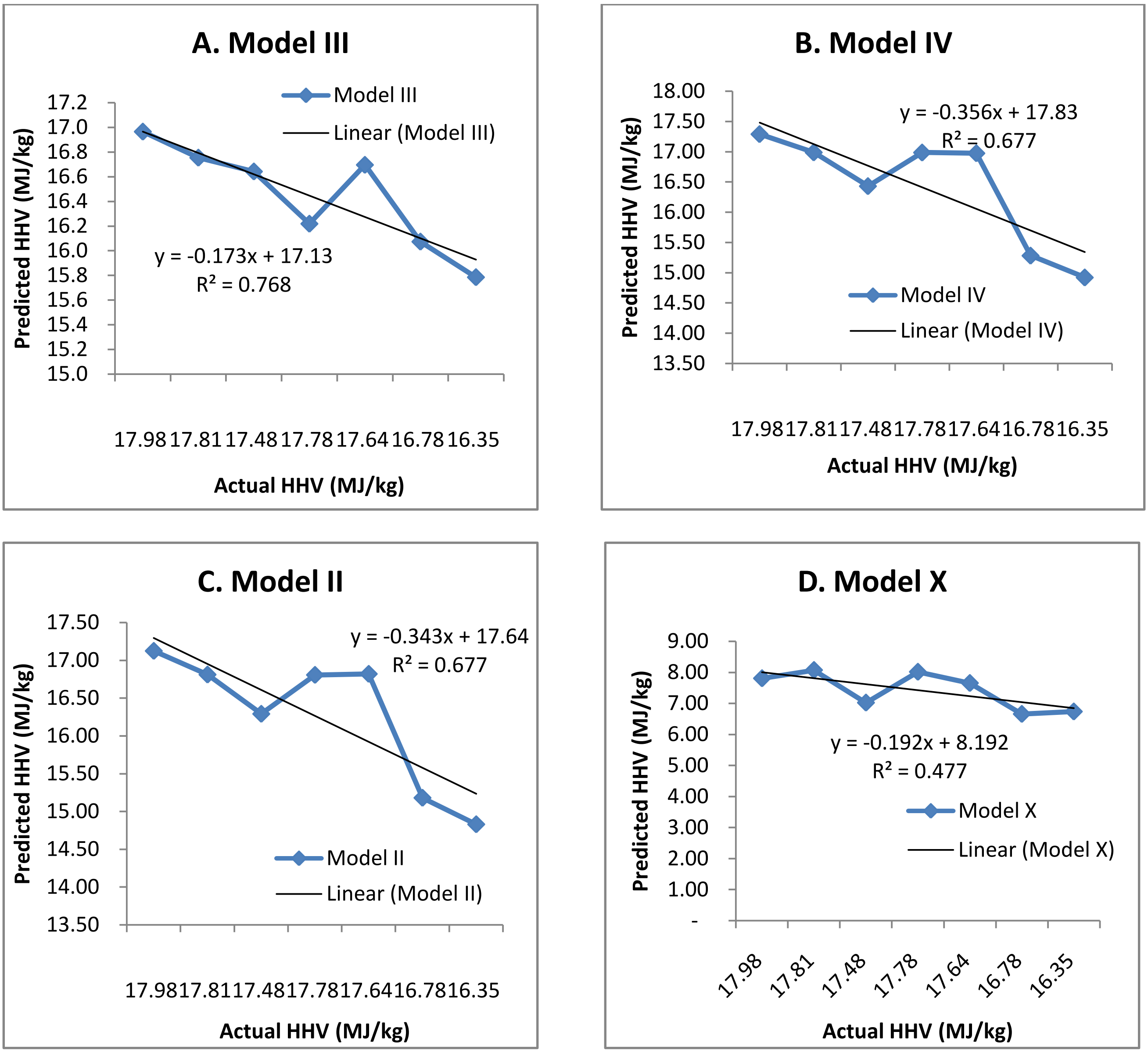

FIGURE 7: R^2 values of selected models from Composition based analysis

IV. CONCLUSION

Physical characterization showed that a high combustible matter and organic waste consisting of food, yard, paper, plastic, wood scrap, and textile waste comprised 91.24% of the total waste of Jimma city household solid waste, suggesting concerting the waste to some economic and environmental characteristics. Estimates of the energy content of Jimma city's household solid waste were made based on Experimental heating and mathematical models developed based on physical composition and proximate analysis. Experimental values led to an estimation of 17.5 MJ/kg for gross heating value, and 9.54 MJ/kg for net heating value which fit the minimum level value required for incineration projects. Generally the heating value of Jimma city household solid waste make it attractive feeds for clean energy production instead of fossil-based solid fuels and can be alternative to the conventional fuels partially due to their high calorific value. The high heating values estimated from selected models were found to be closely matched the value determined experimentally. Therefore, it is concluded that the quantity of energy obtainable from a known amount and composition of solid waste can be estimated without conducting laboratory calorimetric experiments.

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