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# Impact of Moisture Content and Mound Size on Recovery and Quality of Charcoal from *Prosopis juliflora* (SW.) DC. in Rift Valley of Ethiopia

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## ABSTRACT

Determining recovery and quality of charcoal is crucial in Ethiopian conditions where wood-fuel deficit is very high and depletion of acacia woodlands is increasing. The objectives were to investigate the recovery and yield of charcoal per $m^3$ of round wood, and quality of charcoal produced from *Prosopis juliflora* at different moisture content of wood and sizes of traditional earth-mound kiln. The study was conducted by producing charcoal from a naturally grown *P. juliflora* forest in Rift Valley of Ethiopia. 63 $m^3$ of stacked green and 63 $m^3$ air-dried woods were carbonized at 5, 7 and 9 $m^3$ kilns. Quality parameters (proximate value, gross heat value, friability, burning rate, bulk density, spark ignition and smokiness) of charcoal were determined. The result showed a mean recovery of 33.5% and 35% from green and air-dried wood, respectively. Average minimum and maximum yield of charcoal per $m^3$ were 200.9 kg and 227.4 kg from the air-dry and green wood of 9 and 5 $m^3$, respectively. Moisture content of wood significantly influenced ($P < 0.05$) most quality parameters but the difference was non-significant ($P > 0.05$) for recovery, ash content, bulk density and burning rate. Mound size did not significantly affect ($P > 0.05$) both recovery and all quality parameters. Generally, the quality of charcoal was affected by the moisture content, but mound size did not affect both recovery and quality of the charcoal produced from *P. juliflora*.

**Keywords:** charcoal quality, charcoal recovery, moisture content of wood, mound size, *Prosopis juliflora*
**Abbreviations: AC**, ash content; **ADW**, air-dry wood; **BD**, bulk density; **BR**, burning rate; **DBH**, diameter at breast height (1.3 m); **FCC**, fixed carbon content; **GHV**, gross heat value; **GLM**, general linear model; **GW**, green wood; **MCC**, moisture content of charcoal; **MCW**, moisture content of wood; **MS**, mound size; **VMC**, volatile matter content

## INTRODUCTION

The increase in population overtime, and the consequent agricultural expansion accompanied by resettlement have resulted in increasing energy demand and a scarcity of woody biomass; these factors coupled with the rise in oil price have caused great destruction of forests in developing countries (FAO 1978; Asfaw 1990; Melaku 1992; Mekonnen 1999; Behailu 2006; Mulugeta *et al.* 2007). In Ethiopia, forest cover was estimated at 16% in the early 1950s (EFAP 1994a), but had fallen to 3.6% (WBISPP 2004).

According to FAO (1987), the proportion of wood-fuel used to make charcoal was estimated to be *ca.* 25% or about 400 million $m^3$ per annum, throughout the world. More than 90% of the Ethiopian population depends on biomass for its energy requirements (Mekonnen 1999) of which wood-fuel (fuelwood and charcoal) accounts for the greatest proportion (FAO 2005).

The preference and consumption of wood-charcoal, and the demand for it, is continuously increasing with urbanization and with the rise in the oil price (Pasienscznik *et al.* 2001). However, the efficiency of carbonization method customarily used in developing countries is meager. There is a 70% energy loss, which necessitates the clear-felling of increasingly large areas of forest to satisfy the demand (FAO 1987).

Since a large quantity of charcoal in Ethiopia has been derived from the Rift Valley (EEA 1992), the pressure on trees of indigenous woodlands (*Acacia nilotica* and *Acasia tortolis*) of the Afar region has been great (BoA 1998). Hence, improvement of the traditional method of carbonization of wood from *P. juliflora* has its own contribution to produce quality charcoal, and is crucial in averting the current destruction rate of indigenous tree species (WBISPP 1995). Charcoal from *P. juliflora* in the districts of the study area has been produced since 2004 as a remedy to control its invasion of grazing lands, farm lands and indigenous plant species.

Currently, invasion of *P. juliflora* is rampant in the area of the study, after its intentional introduction in 1970's for agro-forestry purpose (Ameha 2006; Anon. 2007). The species threatens agricultural and grazing lands, indigenous riparian tree/shrub species, Awash National Park, irrigation dikes, roads and highways (Senait *et al.* 2004; Ameha 2006). On the other hand, the presence of *P. juliflora,* in Afar and Somali Regions of Ethiopia, appears to provide an opportunity to counterbalance the scarcity of forest and wood resources for charcoal production. For controlling its rampant invasion, studying the potential uses has been crucial (BoA 1998).

There are many opportunities for charcoaling in the study area. Among which availability of the resource (*P. juliflora* wood), existence of highly experienced charcoal-burners, ever increasing charcoal demand and a lucrative charcoal market along the Addis Ababa-Djibouti highway, are the major ones (Anon. 2007). In addition, the fast growth rate of the species and its potential of producing high quality charcoal also are the major merits for the one who will be interested and involved in the business (FAO 1988; Pasiencznik *et al.* 2001).

However, the charcoal-burners in the area use green wood with mound size selected randomly in a traditional earth-mound kiln. This is different from the conventional use of air-dry wood with, an average, seven $m^3$ in trad-

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itional earth-mound kilns in most of the developing countries (FAO 1987).

Recovery of charcoal was higher for higher mound size in earlier monitoring work in the study area from different species (Anon. 2004). In addition, using green wood affects the recovery of charcoal by consuming more of the wood charged to remove the moisture (Foley 1986).

Even though some researchers have been carried out on fuelwood characteristics of some *Acaci*a and *Eucalyptus* species of central Rift Valley (Birhanu 1996; Woldeyohanes *et al.* 2007), there has been no investigation made whether moisture content and mound size has effect on the recovery and quality of charcoal produced from *P. juliflora*, under Ethiopian conditions.

Hence the study was conducted in Amibara district of Afar National Regional State (ANRS) (found in Rift Valley of Ethiopia) to determine the effect of moisture content of wood and mound size on recovery and quality of charcoal, to compare the current charcoal making practice (green wood) against the conventional ones (air-dry wood); and to estimate the yield of charcoal per $m^3$ of green wood, produced from *P. juliflora*.

## MATERIALS AND METHODS

### Experimental site description

The study was conducted in ANRS at Amibara district (09°16'-09°21' N and 40°08'- 40°12'E), Bedulali Kebele, which is situated at about 260 km North East of Addis Ababa. The range of altitude in the district is between 740 and 820 m asl. The district has a total annual rainfall of 564 mm which is less than the total annual average evapo-transpiration of 2050 mm. Hence, the area has an average annual moisture deficit of 1486 mm. The mean annual temperature of the area is 34.1°C (Anon. 2006).

The main geo-morphological unit of the district is characterized by an alluvial plain. The soil, however, is mainly dominated by Eutric Fluvisols. Vertisols are the second dominant soil (Tadesse and Abegaz 1996). Lithosols predominate only on steep slopes and eroded hills (Shiferaw *et al.* 2004). The soil profiles show sodic properties with a high accumulation of soluble salts at the surface of the mineral soil (Tadesse and Abegaz 1996).

The vegetation of the district is dominated by dense riparian forests, in particular; *Acacia nilotica* and *Tamarix aphylla* following the bank of the Awash River. However, *P. juliflora*, which is believed to be introduced in to the study area in 1970's, rapidly invades almost the entire grazing land, farm boundaries, roadsides and riparian forests. Shrub land, open land and grassland are the major types of vegetation covering 38, 30 and 19% of the total land area, respectively. Livestock is the major livelihood base for the region (WBISPP 2003). Cotton is the major crop grown by state and private investors along the Awash River where irrigation is possible.

### Experimental design

A total of 18 experimental units were considered in the experiment. The design of the experiment was 2 × 3 factorial completely randomized design (CRD) with three replications. The two factors were two levels of moisture content of wood (MCW) before carbonization, vis. green wood (GW) and air-dry wood (ADW); and three levels mound size (MS) of traditional earth-mound kiln, vis. 5, 7 and 9 $m^3$. The selection of the size of the mound kilns used in the experiment was based on the variation in size of the pile in traditional earth-mound kilns, from 5 up to 8 $m^3$, for most charcoal–burners in developing countries (FAO 1987).

### Selection, preparation and measurement of stand and round wood

*P. juliflora* stand, grown naturally with an estimated age of *ca.* 10-13 years old (information from key informants) was selected. Matured trees suitable for traditional charcoaling were selected and marked; their height and diameter at breast height of all the marked trees were measured, number of stems per stump counted, and finally clear felled.

A total of 126 $m^3$ stacked volume round wood of *P. juliflora* was harvested from 1st December to 30 January, 2008 (dry season). 63 $m^3$ of the total stacked wood was used as green wood and the remaining 63 $m^3$ as air-dry wood. The 63 $m^3$ of the green wood was stacked in 5, 7 and 9 $m^3$, and arranged in three replications. The same method was followed for stacking and arranging the experimental groups for the remaining 63 $m^3$ of air-dry wood.

The minimum diameter of the stem or branch carbonized was 2 cm. Thorns of the felled trees were first removed by means of machete and crosscut in to one meter lengths using axe, and stacked in 1 $m^3$ in order to estimate the volume of each mound. The weight of the whole wood stacked in $m^3$ was measured by means of a 100 kg balance. Then, the measured wood (in terms of volume and weight) was stacked in the open air to dry for one month, with stickers inserted to allow air to circulate throughout the stack. After one month of drying, the whole ADW was re-weighed again by means of a 100 kg balance. For the GW treatment, however, the felled fresh wood was immediately weighed, piled and fired before losing its moisture.

The mounds were piled based on the experience of the local charcoal-burners in which, the shape of the mound was wide at the base and narrow at the top. The soil cover was thin at the base for air inlet until the heat was stable and sealed afterwards. The mound was sealed by plant leaf and soil following the leakage. All piles were fired at 6:00 A.M. in the morning.

### Determination of wood moisture content of *P. juliflora*

Moisture content of both the GW and ADW was measured before carbonization, by taking representative samples of discs from the wood used for the carbonization. For this purpose, a total of 18 representative trees were randomly selected and marked from the stand in three diameter classes 2-4, 4-6 and 6-8 cm. Nine samples of the total 18 trees were used for the GW, and the remaining nine for ADW. Each diameter class was replicated three times both for GW and ADW.

All the selected and marked trees for sampling were felled at the same time. Twenty seven discs of 3 cm long were cut from the bottom, mid- and top of each sample tree both for the GW and ADW. For the GW, the discs cut were labeled, placed in paper bags and packed to reduce excessive moisture loss, and immediately taken to the Laboratory for determining the MCW. For the ADW, however, the remaining nine sample trees were kept together with the stacked wood to dry in the open air for laboratory processing held one month after air-drying. MCW was determined based on International Standard-ISO 3130 (ISO 1975). The volume of debarked discs was determined by the water displacement method (Heinrichs and Lassen 1970) using 500 ml graduated cylinders.

### Determination of volume coefficient of stacked wood of *P. juliflora*

The volume coefficient of stacked wood is that portion of volume in the stacked wood occupied by air space. Volume coefficient of 1 $m^3$ stacked GW was determined by water displacement method (Heinrichs and Lassen 1970).

### Stacking and carbonizing process

Stacking and carbonization process of the GW was handled side by side following the same procedure as used for the ADW. After carbonization was complete, the mounds were opened for unloading and cooling for 12 hrs. Cooling and unloading were supported by drawing some of the soil from the base, and gradually mixing the burned soil with the charcoal with a rake. The burned soil, which was used to cover the mound itself, was used for suppressing the fire during unloading. Unburned wood and charcoal were separated manually, and weighed with a 100 kg balance, after sacks were filled in the same way as when they are locally delivered for market.

**Table 1** Weight basis mean value of charcoal yield and recovery in two levels of MCW and three levels of MS from *P. juliflora* round-wood grown in Rift Valley of Ethiopia.

| MCW | MS | Yield ($kgm^{-3}$) | ±SE | Recovery (%) | ±SE | Weight of 50-kg bag (kg) | ±SE |
|---|---|---|---|---|---|---|---|
| GW | 5 | 227.4 a | 7.27 | 33.2 a | 0.36 | 30.3 ab | 0.53 |
| GW | 7 | 210.9 a | 3.22 | 33.5 a | 1.05 | 30.6 a | 0.35 |
| GW | 9 | 211.5 a | 11.89 | 34.03 a | 1.13 | 30.6 a | 0.03 |
| ADW | 5 | 205.6 a | 17.91 | 34.8 a | 2.76 | 29.0 bc | 0.7 |
| ADW | 7 | 203.5 a | 10.2 | 35.07 a | 0.94 | 29.0 bc | 0.94 |
| ADW | 9 | 200.9 a | 1.1 | 35.2 a | 0.64 | 28.7 c | 0.15 |

CV for yield is 8.43 after running ANCOVA, and for Recovery is 6.95 and for Weight of 30-kg bag is 3.17 after GLM, n = 18
GW: green wood, ADW: air-dry wood, 5, 7 and 9: sizes of mounds ($m^3$), MCW: moisture content of green wood, MS: mound (pile) size, SE: standard error of mean
Means with the same letters within a column are not significantly different
**NB.** The volume ($m^3$) refers to the true volume obtained after multiplying by stacking volume coefficient (ca. 0.496), determined for the experiment.

## Sample collection and preparation

Representative samples of charcoal were collected and mixed in a double layer sack from all portion of the mound. One kg charcoal from each sample was grinded gently and prepared for proximate analysis, bulk density and calorific value determination. For the mechanical and physical parameters (friability test and burning rate), however 15 kg sample were collected from each mound and put in a double layer bag until used for the tests.

## Estimation of quantity and quality parameters of charcoal

Weight of the charcoal produced was registered and the number of sacks of charcoal produced was counted. Recovery of charcoal (dry basis mass yield) was determined based on the suggestion of Boutette and Karch (1984).

Proximate analysis (including moisture content of charcoal (MCC), volatile matter content (VMC), ash content (AC) and fixed carbon content (FCC) was carried out by following the procedure and standards in American Standards for Testing and Materials Designation (ASTM D) 1762-84 (Re-approved 2007) (ASTM 2007).

The bulk density of charcoal fines indicates the weight of the charcoal fines, per unit volume, and is important for shipment calculations. For determining bulk density, ASTM D 1762-84 (Re-approved 2007) (ASTM 2007) was followed.

Gross heat value (GHV) of the charcoal produced was determined by bomb calorimeter, following the operating instruction of Parr Adiabatic Bomb Calorimeter based on ASTM D 2015 (ASTM 1998). Benzoic acid was used for the calibration of the calorimeter. The calorimeter used was a microprocessor-based instrument, which utilizes the isothermal method for measuring the calorific value. The same samples as prepared for proximate analysis were used to determine the GHV.

The rate of burn of the charcoal samples was determined by the water boiling test following the procedures used at the Ethiopian Rural Energy Development and Promotion Center (EREDPC). Spark and smoke characteristics of the burning charcoal were observed and noted. Then burning rate (BR) of charcoal was calculated as BR (g/min) = Wt / T, where BR = burning rate, Wt = weight of charcoal (sample), T = time elapsed.

Charcoal strength (the percentage loss) was tested at the EREDPC. Charcoal samples were tumbled in a drum 60 cm in diameter, rotating at 22 revolutions per minute (RPM), to test the friability of the charcoal. Percentage loss was determined as friability (%) = [(A - B) / A] × 100) where, A = gram of lump sample before tumbling, and B = gram of lump sample after tumbling.

## Data analysis

The arithmetic mean values of charcoal production, recovery and quality parameters, for both MCW and MS, were used to test the statistical significance. The yield of charcoal was expressed in terms of recovery (conversion efficiency) of charcoal from round wood and yield of charcoal per $m^3$ of round wood. The quality parameters of charcoal considered were GHV, MCC, VMC, FCC, AC, BD, BR and friability test.

Finally, yield results were tested for their significance using Analysis of Covariance (ANCOVA) considering the variation of initial green round wood weight from the same sizes of mound as a covariate. However, the recovery, weight of 50-kg bag, and all charcoal quality parameters were tested using General Linear Model (GLM), at 95% confidence level, between ADW and GW, and among three levels of MS of traditional earth kiln using Statistical Analysis System (SAS-V8). Duncan's Multiple Range Test (DMRT) (SAS-V8) was employed to compare treatment means.

# RESULTS AND DISCUSSION

## Yield and recovery of charcoal from *P. juliflora*

Yield of charcoal per $m^3$ calculated volume wood of *P. juliflora*, was determined on green weight basis of round-wood. The present study estimated that an average of 216.6 and 203.3 kg of charcoal produced from 1 $m^3$ calculated volumes of GW and ADW, respectively. The highest value (227.4 kg) of charcoal yield per $m^3$ was obtained from GW in 5 $m^3$ mound; whereas the least value (200.9 kg) was from ADW of 9 $m^3$ (**Table 1**).

The average recovery of charcoal was *ca*. 33.3% and 35% from GW and ADW, respectively. The highest mean value of charcoal recovery (35.2%) was obtained from ADW of 9 $m^3$ while the lowest (33.1%) was from GW of the same MS. This means an average of 2.8 kg of ADW and 3 kg of GW is required to produce 1 kg of charcoal. The results (**Table 1**) had shown that there was no significant difference ($P > 0.05$) of charcoal yield and recovery, both between MCW and among different MS. Also there was no interaction effect between MCW and MS ($P > 0.05$). However, the weight of 50-kg bag varies significantly ($P < 0.01$).

The reason for the insignificant different response of recovery from different MCW may be the very small amount of difference in MCW to cause impact. Because, in the present study, mean MCW used before carbonization was determined to be 21.2% when green and 12% after one month of air-drying with only 9.2% moisture loss. The very hot climate (18.9-38°C) causing moisture stress to the species and dry season of harvesting (December to January) may contribute for the very low MCW when green.

The value of MCW varies with species, genetic differences, tree components used, age and growing conditions (Pasiecznik *et al.* 2001; Woldeyohanes *et al.* 2007). Similarly, MCW for *P. julilora* vary highly depends on growing sites (Pasiencznik 2001). The very high average annual moisture deficit (1486 mm) (Anon. 2006) at the study area might contribute for this low value of MCW (mean of 21.2%), unlike that of the average MCW for most woody species (50%) when green (FAO 1985).

The higher the weight per $m^3$ of charcoal from GW does not imply the higher charcoal recovery as the weight may be caused by moisture content of the charcoal (negative parameter). Although the yield (weight) per $m^3$ in ADW seems less than that of the green wood, the recovery (more appropriate indicator) and the 50-kg bag weight were resulted in the reverse.

Moreover, 50-kg bag charcoal on an average weigh 30.5 kg when produced from GW, while it weighs 28.9 kg if produced from ADW. Which means charcoal from GW weighs 1.6 kg over the ADW for every 50-kg bag while volume package is the same, irrespective of the MS. This indicates that charcoal from GW requires additional transportation cost to carry the extra load compared to charcoal from ADW.

Charcoal recovery results (33.1-35.2%) of the present study exceed the range (20-33.3%) of studies elsewhere (Pasezcink *et al.* 2001). The range of recovery of previous monitoring work in Amibara district of ANRS (Anon. 2004) was 24-31% for different MS of traditional earth-mound kiln in the area, using *A. tortolis*, *A. nilotica* and *P. juliflora*, although the test was conducted in non-replicated manner (Anon. 2004). This variation was very high compared to the result of very small variation (33.1-33.5% for GW, and 34.8-35.2% for ADW) among MS of the present study of the same area. In addition, the efficiency of charcoal in the present study was by far greater than the record from traditional earth-mound and earth-pit kilns obtained (8-12%) in the country before (Anon. 2004).

The result of the present study among MS was within the range of the previous monitoring work (Anon. 2004), which shows the consistent relationships between the two studies. However, the present study revealed that the variation was insignificant ($P > 0.05$), within and between both factors; i.e., MCW and MS. This signifies how important is making replication to test the significance, which the previous monitoring work lacked.

## Quality of charcoal from *P. juliflora*

### *1. Proximate analysis*

The mean results of proximate characteristics of charcoal were presented in **Fig. 1**. The majority these quality parameters were significantly different ($P < 0.05$) between MCW; whereas the difference among MS was not significant ($P > 0.05$) for all quality parameters.

The FCC of charcoal in the present study was in the rage of 64.9% and 75.3%. GLM and DMRT test results revealed that this variation was significant ($P < 0.001$) between MCW but it is insignificant ($P > 0.05$) among MS used in the investigation (**Fig. 1A**). Also Interaction effect was not significant.

The usual variation in FCC of charcoal in other studies was in the rage of 50 to 95% (FAO 1987). It was also described in the same document that VMC of good quality charcoal was about 30% indicating that the FCC of the same sample of charcoal must be less than 70%. Because of FCC of charcoal is obtained by deducting the sum of percentage composition of MC, AC and VMC from 100%. When 30% of VMC, 3% of AC and mid-value of 7.5% MC of good quality charcoal, are deducted from the total 100%, about 60% remains which is considered the FCC value of good quality charcoal. Hence from the present study, better results of FCC of charcoal was observed for ADW in 7 $m^3$ of MS (64.9%), followed by 9 $m^3$ of ADW (67.2%).

The Mean values of VMC of charcoal and test statistics are presented in **Fig. 1B**. The highest VMC of charcoal was obtained from 7 $m^3$ of ADW (25%), while the least (13.8%) was from 5 $m^3$ of GW (**Fig. 1B**). This value of VMC in ADW was in the range of the usual variation of VMC (20-30%) in household consumed charcoal (Anon. 2004). This comparably higher value of VMC of charcoal in ADW may be due to the lower amount of MCW used, which requires short period of carbonization. This means the lower the MCW, the lower the time taken for the carbonization process; hence, the higher the VMC of charcoal will be obtained (FAO 1987). In the present study, only 4 to 7 days were elapsed for the complete carbonization process for ADW, compared to the elapsed time of 6 up to 11 days for the GW, depending on the MS.

The variation in VMC of charcoal was highly significant ($P < 0.001$) between MCW. However, VMC among MS and interaction effect were not significantly different ($P > 0.05$). The difference in VMC of charcoal between 7 and 9 $m^3$ of GW was not significant but significantly different from 5 $m^3$. All the three MS of GW were significantly different from that of all MS of the ADW in VMC of charcoal.

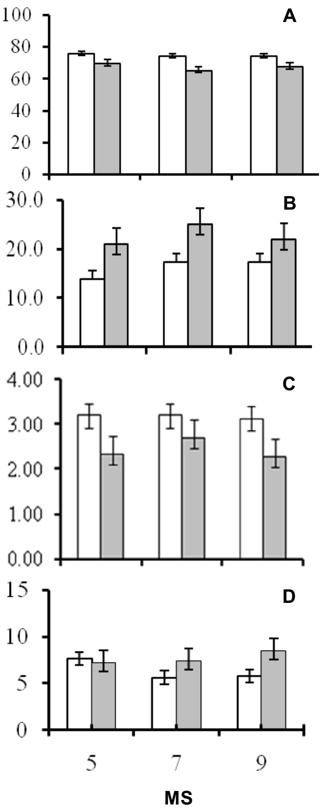


**Fig. 1** Mean fixed carbon content (FCC) (%) (**A**), volatile matter content (VMC) (%) (**B**), moisture content (MC) (%) (**C**) and ash content (AC) (%) (**D**) of charcoal for MCW and MS used in carbonization, from *P. juliflora*, grown in Rift Valley of Ethiopia. GW = green wood (white bars); ADW = air-dry wood (grey bars); MCW = moisture content of wood; MS = mound size; 5, 7 and 9 = sizes of mounds ($m^3$), n =18.

The higher the VMC of charcoal to 30%, the best the quality, and burns easily the charcoal is. In general, all values of VMC of charcoal in the present study were below the commercial quality specification of 30% although the range of VMC varies between 5 and 40%, in other studies elsewhere (FAO 1987). However, it does not mean charcoal from the present study is poor in quality. Rather, one pile showed 28.8% VMC of charcoal in ADW.

This value indicates the possibility of increasing the VMC of charcoal to the commercial quality specification by drying the wood before carbonization. In all the three MS of ADW, the value of VMC was above the mid- value of the range (5-40%) given above. This also indicates how important is drying the wood before carbonization; since all the three MS of GW was below the mid value of the range compared to all the three MS of the ADW. The results revealed that ADW was by far better in VMC of charcoal than that of GW but making the size of mound different had no significant impact on VMC of charcoal from *P. juliflora*, carbonized in traditional earth-mound kiln. Charcoal from *P. juliflora* in the present study therefore exhibited good quality when carbonized after air-drying for one month in the study area.

The highest MC of charcoal was observed for 5 and 7 $m^3$ of GW while the lowest in 9 $m^3$ of ADW (**Fig. 1C**). Moreover, from both GW and ADW, the highest MC was observed in 5 and 7 $m^3$, followed by the 9 $m^3$. The result of the present study revealed that MC of charcoal from the MCW under this investigation varied significantly ($P < 0.01$) but it was totally insignificant for MS ($P > 0.05$). The MC of charcoal from GW of all the three sizes of mounds also did not exhibit significant variation from ADW of 7 $m^3$.

Generally, the value of MC of charcoal from all treatments of the present study was nearly similar to, or below the commercial quality specification (about 3%) of lump charcoal (FAO 1987). The low value MC of charcoal in the present study may be due to the low humidity in the study area. This means MC could be increased to 15% by absorbing air moisture in humid environment (FAO 1987). In terms of moisture content, traditionally produced charcoal from *P. juliflora* can be termed as high quality charcoal, irrespective of MCW and MS.

The range of AC of charcoal in the current study was between 5.6 and 8.5% with the highest mean value was from 9 $m^3$ of ADW and the lowest from 7 $m^3$ of GW (**Fig. 1D**). Ash content of charcoal vary widely in the range 0.5-10% depending on the method of carbonization, the amount of bark included during carbonization and the extent of soil contamination, with about 3% being considered good quality charcoal (FAO 1987). The present study showed a high AC of charcoal from *P. juliflora* carbonized in different MCW and MS of traditional earth-mound kiln (**Fig. 1D**).

Although the mean value of all treatments in the present study was in the range (5.6-8.5%), they were above the considered 3% of AC of good quality commercial purpose charcoal. The highest AC of charcoal in the present study might be explained by the contamination of soil with the lump charcoal during carbonization process, particularly when charcoal was unloaded. In the present study, grass or leaves of plants lay between the soil and the wood, were used to suppress fire during carbonization, which probably increases the contamination level of the charcoal. The other reason for the higher ash content of the charcoal can be explained by the very high accumulation of salts in the tissue of *P. juliflora* wood, because the soil of the study area is affected by salinity and high evapo-transpiration problem.

The variation in AC of charcoal was not significant ($P > 0.05$) at all for both factors considered; MCW and MS. Of course, the p-value for MCW is 0.0583 (on the margin). The explanation given in FAO (1987) was similar to the results of test statistics (non significant difference) of the present study for AC of charcoal (**Fig. 1D**). That is, usually, AC of charcoal does not significantly vary among different species and different carbonization methods used (FAO 1987). A minimum AC of charcoal record in one pile of the present study was 3.6%, which is nearly a good quality charcoal specification. This implies the existence of the opportunity of reducing the AC of charcoal from *P. juliflora* by decreasing the level of contamination of soil.

## *2. Thermal and physical characteristics*

Mean values of thermal and physical characteristics of charcoal is presented in **Fig. 2.** The highest mean GHV (7243.8 Cal/g) was obtained from 9 $m^3$ while the lowest (6780.0 Cal/g) from 5 $m^3$ of GW. GHV of charcoal was significantly different ($P < 0.05$) between MCW, but not among mound sizes (**Fig. 2A**). Also, the interaction effect of the two factors was not significant ($P > 0.05$).

The present study showed that charcoal from *P. juliflora* had better GHV (7243.8 Cal/g) from 9 $m^3$ of ADW compared to the mean value (7081 Cal/g) of heat of three *Acacia* species carbonized by metal kiln (Birhanu 1996). This implies that *P. juliflora* is among the best tree species for charcoaling. The higher the calorific value of *P. juliflora* in general can be described by the very low moisture content (mean of 21.2%) and higher bulk density (mean of 0.95 g/$cm^3$).

A study conducted on fuel characteristic of six woody species showed a minimum of 38% MC and a maximum of 0.53 g/$cm^3$ bulk density (Woldeyohanes *et al.* 2007). Compared to this study, *P. juliflora* can be suggested excellent wood-fuel species in Ethiopian context.

GHV of ADW exceeds that of the GW for all MS. The result had revealed the impact of drying wood before carbonization by increasing the GHV and VMC of charcoal compared to the use of GW. From the present study charcoal-burners are advised to dry the wood of *P. juliflora* before carbonization.

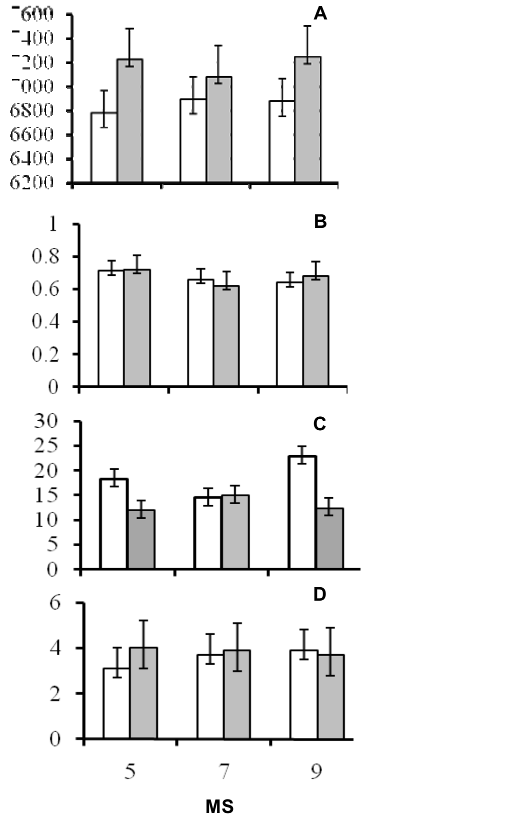


**Fig. 2** Mean gross heat value (GHV) (Cal/g) (**A**), bulk density (BD) (g/ccm) (**B**), friability (%) (**C**) and burning rate (BR) (g/min) (**D**) at boiling temperature of charcoal for MCW and MS used in carbonization, from *P. juliflora* grown in Rift Valley of Ethiopia. GW = green wood (white bars); ADW = air-dry wood (grey bars); MCW = moisture content of wood; MS = mound size; n = 18.

Considering the relationship between VMC and FFC with their corresponding GHV, charcoal with a high VMC (in ADW) resulted in a high GHV than charcoal with a high FCC (in GW). For example, the mean value of FCC from GW of 5 $m^3$ (**Fig. 1A**) in this treatment was the highest of all other treatments; but the same treatment had resulted in the least value of VMC and GHV than all other treatments.

Results of woodfuel study elsewhere (Sandberg 1985; Birhanu 1996) showed the same differences in VMC and FCC, with the corresponding value of GHV. Sandberg (1985) had explained the difference that charcoal with high VMC can have greater heating value than charcoal with high FCC. This was explained by the difference in calories obtained from carbon (7 Kcal/g) and hydrogen (34 Kcal/g).

The range of bulk density of powdered charcoal was between 0.63 g/$cm^3$ and 0.73 g/$cm^3$. The difference was not significant ($P > 0.05$) both for MCW and MS (**Fig. 2B**). The higher the bulk density, the higher the transportation cost for those who export charcoal (FAO 1987). In commercial charcoal production, bulk density is considered as one factor that affects the price of charcoal on the market.

In the present study, the highest loss of charcoal was recorded in GW of 9 $m^3$ while the least from ADW of 5 $m^3$ (**Fig. 2C**). The difference was significant ($P < 0.05$) between MCW whereas insignificant ($P > 0.05$) among MS. And there was no interaction effect between MCW and MS. Friability of charcoal is a loss of charcoal due to being broken into pieces and considered as negative entity. The 9 $m^3$ of MS from GW was exceptionally significant in difference from all MS, irrespective of MCW. Charcoal produced from GW resulted in a higher loss with mean value being 18.6% (in the range of 12.2-30.2%) compared to a mean value of 13.2% (in the range of 9.0-15.0%) from ADW. Generally, the present study revealed that drying the wood was paramount when charcoaling for enhancing the quality of charcoal in terms of friability.

Results of burning rate (g/min) tested at boiling temperature were presented in **Fig. 2D**. There were no significant differences both between the two levels of MCW and among different sizes of traditional earth-mound ($P > 0.05$).

Qualitative characteristics such as spark ignition and smoke of charcoal were also noted during determination of burning rate. Charcoal produced from GW showed a high and continual spark ignition, compared to that of ADW. In ADW, however, spark ignition observed only until lightening completes and seizes afterwards. But there were negligible smoke observed from charcoal produced either from GW or ADW. This is because of the medium content of VMC consisting of pyroligenous acid in the charcoal of all samples.

Even though there was no significant difference ($P > 0.05$) observed between MCW and among MS (**Fig. 2D**), there was an increasing pattern of rate of burn with increasing the size of mound for GW at boiling temperature. However, the reverse was true for ADW. When comparing the 9 $m^3$ MS between GW and ADW, the latter burns moderately than the former. Moreover, moderately burning charcoal is favored both for its economic use and its effect on cooked food.

Only three (GW 7 and 9, and ADW 7 $m^3$) mounds of the total 18 did not show any spark ignition either at the beginning of combustion or long lasting to the end. But the main difference observed was that charcoal sample from ADW had spark ignition at the beginning of heating only in contrast to the longer lasting effect of charcoal sample from the GW, irrespective of MS. This means, charcoal from ADW sparked until completely lightened (ignited) and seized afterwards; but charcoal from GW samples continued to spark to the end, irrespective of combustion time. This is because of a comparably higher FCC of charcoal from GW sample than from ADW.

The evenly and moderately burning characteristics of charcoal from *P. juliflora* of ADW might be the result of its ambient chemical composition (not very high VMC (40%) to cause charcoal burnt and completed fast, and not very high FCC (95%) to cause charcoal friable and sparking.

## CONCLUSIONS

The yield of charcoal per $m^3$ of round wood of *P. juliflora* was in a range of 200 kg and 227 kg depending on the MCW and MS used for carbonization. The best recovery of charcoal was obtained from ADW in 9 $m^3$ MS of traditional earth-mound kiln. The value of this recovery was 35% i.e., 1 kg of charcoal produced from 2.8 kg of green wood after drying in open air for one month. However, the variation in recovery of charcoal was not significant ($P > 0.05$) between the two levels of MCW and among MS used in carbonization.

The present study concluded that drying GW of *P. juliflora* in an open air for one month duration before carbonization had significant effect ($P < 0.05$) on quality parameters of charcoal such as MCC, VMC, FCC, GHV and friability. Mound sizes, however, had no significant effect ($P > 0.05$) on yield, recovery and quality parameters.

Some qualitative characteristics had shown that charcoal from *P. juliflora* produced some sparks for ADW at the beginning of lightening and seized after a little while. However, for charcoal produced from GW, spark ignition lasts longer during combustion. Almost no smoke has been observed during burning of charcoal from *P. juliflora* irrespective of MCW and MS used for carbonization. The present study therefore summarized that better recovery and good quality charcoal, from *P. juliflora*, was obtained from ADW than that of GW. This study also advised charcoal burners from *P. juliflora* to dry the wood before burning.

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