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SELECTION OF AN APPROPRIATE BIOMASS BURNER FOR DRYING MAIZE IN A CROSSFLOW COLUMN DRYER USING AN ANALYTIC HIERARCHY PROCESS

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Abstract. *Several post-harvest technologies have been introduced over the past years to help smallholder farmers in sub-Saharan Africa reduce crop losses. However, not all these technologies fit the same application purpose to meet the needs of farmers in different locations. This study, therefore, applied a multi-criteria decision method, the analytical hierarchy process (AHP), to select an appropriate biomass burner based on its technical performance, cost, and design criteria to complete the setup of a low-cost column dryer. With a priority value of 0.69 out of 1.00, the KNUST-ABE Biomass Burner was selected over the AFLASTOP Biomass Burner which had a priority value of 0.31 out of 1.00. Based on the results of this study, the AHP multi-criteria decision method was helpful in the selection of a locally developed biomass burner for a low-cost column drying system.*

Keywords: *drying technology; biomass burner; multi-criteria decision making; analytical hierarchy process*

1. Introduction

Among many staple crops grown in Ghana, white maize grain is by far the most cultivated and consumed staple grain and contributes significantly to consumer diets (Darfour & Rosentrater, 2016). It is grown in many agro-ecological zones in Ghana, and it is a good source of carbohydrates in meals (Akowuah *et al*., 2015). Although maize plays an important role in ensuring food and nutrition security in Ghana, it faces substantial post-harvest challenges in the aspects of storage and preservation (Kumar & Kalita, 2017).

Drying plays a major contributor to the 30% loss associated with maize due to post-harvest handling (Bosomtwe *et al*., 2019). It is a common practice in Ghana for grains to be dried in the open sun as farmers dry crops in the field, laying them on the bare ground or on tarpaulins (Akowuah *et al.*, 2018). Often, weather conditions during this period are highly unfavorable to carry out the drying process because this period coincides with the rainy season (Danso *et al.*, 2017). In situations like these, grain drying can take more than five days. Prolonged delay or intermittent drying during such periods causes a series of wetting and drying cycles before the grain is finally dried. Under these conditions, mold and mycotoxin contamination of the food grain is inevitable, leading to substantial loss.

Due to the high installation and operational cost of mechanical and electric drying systems, the search for low-cost batch drying systems has been a priority for most smallholder farmers to meet

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their drying needs. Prototypes of such low-cost batch drying systems developed elsewhere for smallholder farmers (Chua & Chou, 2003) are gradually being introduced in Ghana. Among such drying systems are the Solar Bubble Dryer developed by GrainPro Inc.(Asemu *et al.*, 2020), the AflaSTOP dryer developed with support from the Gates Foundation (Owusu-Sekyere *et al.*, 2021), and the STR dryer developed under the USAID Post Harvest Loss Reduction Innovation Lab (PHLIL) (Saha *et al*., 2017).

The availability of all these appropriate drying systems for smallholder farmers poses an onerous decision-making problem where farmers would have to select a suitable drying system for their needs depending on various factors: geographic location, capacity, cost, dryer configuration or setup, and many others. Multi-criteria decision analysis (MCDA) has been utilized in instances where several alternatives can be used to address a specific problem (Hruška *et al.*, 2017). The analytic hierarchy process (AHP) is one of these MCDA methods (Saaty 1980; Saaty 1994), which has been developed for ranking problems and occasionally for choice problems. As a methodology for assessing the ranks of alternatives, AHP creates a final problem by separating decision-making into many sub-problems that are equal and can be solved by recapping sub-problems in which results of the initial problem are evaluated (Improta *et al*., 2018; Steuer & Na 2003).

In this study, AHP was applied as a tool in the selection of a portable biomass burner that would meet the need for serving as a heat source in some low-cost batch drying units available for smallholder farmers in Ghana.

2. Methods

2.1. Theoretical development

2.1.1. Analytical hierarchy process (AHP)

AHP provides a systematic approach for the selection of one alternative out of a whole lot of different alternatives based on various criteria (Hruška *et al.*, 2014). As a theoretical process, AHP applies both qualitative (e.g., decision makers' experience, survey, consultancy, and extensive literature reviews) and quantitative (use of experiments) techniques to develop weights for each alternative under consideration and out of these weights, decision-makers can make appropriate decisions (Mu & Pereyra-Rojas, 2017). The Analytical Hierarchy Process was carefully developed through psychology and mathematics by (Saaty 1980), and since then, has been refined and applied in various fields ranging from marketing and supply chain management (Hruška *et al.*, 2014; Salomon *et al.*, 2016), medical (Improta *et al.*, 2018), renewable energy (San Cristóbal, 2011), agro-environmental (Giri & Nejadhashemi, 2014) to engineering (Jorge *et al.*, 2015).

2.1.2. The AHP procedure

The procedure which was adopted from studies by (Jorge *et al.*, 2015) are as follows;

Step 1--- Decision modeling: The biomass burner selection process was modeled figuratively as shown in Figure 1, with the expected goal to be achieved placed at the top followed by the criteria for the selection process, sub-criteria, and finally, the biomass burner alternatives for the study. The decision model provides a clear decomposition to understand better the purpose of the selection process based on the alternatives available.

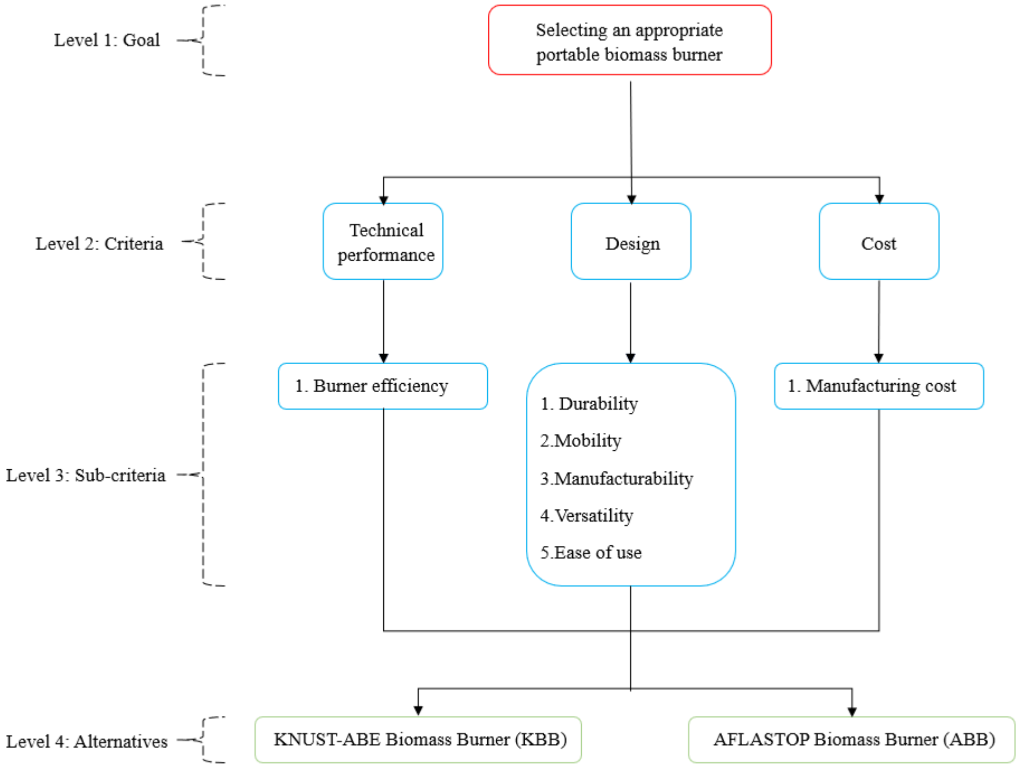


Figure 1. Decision model for selectin biomass burner alternative

Step 2--- Pairwise comparison: Decision-making elements, particularly factors in the sub-criteria, were compared in a pairwise manner in terms of importance. This comparison resulted in the allocation of numerical values, also known as the weight of importance following the Saaty Fundamental Scale (T. L. Saaty, 1980), as shown in Table 1.

Table 1. Fundamental Scale of Thomas L. Saaty (T. L. Saaty, 1980)

Scale	Definition	Description
1	Equally important	Two elements have the same importance
3	Moderate importance	An element is slightly more important than another element
5	Obviously important	An element is obviously more important than another element
7	Particularly important	An element is dominant
9	Absolutely important	An element is absolutely important/position of dominance
2,4,6,8	Between the adjacent Judgment	Between the importance of 1,3,5,7

Step 3--- Creation of the pairwise comparison matrices: The weight of one element relative to the other at each level was computed as a component of a normalized vector coupled with the highest value of the comparison matrix. The Consistency Ratio (CR) which gives an indication of the level of consistency in the creation of the matrices, was calculated. The calculation of CR considers one entry over another in the matrix, and as such, a low CR value ($CR \leq 0.1$) indicates a good decision (Giri & Nejadhashemi, 2014).

Step 4--- Calculation of composite weights: The weight of each alternative was added throughout the hierarchy, from top to bottom, and multiplied by the actual weight of each criterion. This resulted in the composite weight which gave the global weights of the alternatives.

2.1.3. Application of the AHP in the study

As elaborated in Table 2, considerations were made in the selection of the appropriate biomass burner. The relative status of these criteria with respect to the goal of the study was given a weight based on procedures outlined by (Aşchilean *et al.*, 2017).

Table 2. Description of all decision sub-criteria and their objective in achieving our stated goal

Symbol	Sub- Criteria	Objective	Description
C1	Burner efficiency	Maximized	This defines the technical performance of the system, and as such, takes into consideration the effectiveness of the heat exchangers and, the consumptive use of energy by the system.
C2	Ease of use	Minimized	This defines the safety of using the system. Aspects considered were exposure of operators to moving parts of the system, the generation of smoke from combustion and the noise made during operational procedures.
C3	Cost of manufacture	Minimized	This defines the cost of all materials required for the manufacture of the system.
C4	Durability	Maximized	The selected burner should last long amidst handling on farms and operation in remote areas.
C5	Mobility	Maximized	The selected system should be easily transported from one drying station/farm to the other.
C6	Manufacturability	Minimized	This measures the ease of manufacture of the biomass burner. The expertise, material required, and manufacture recommendations should comply with that of the local artisans' comfort.
C7	Versatility	Maximized	How compatible is the biomass burner with other drying systems? Can it be applied to other dryers without any modification in its design?

2.2. Experimental study

2.2.1. The column dryer with the portable biomass burner alternatives

The two portable biomass burners alternatives of which one needed to be selected for incorporation into a column dryer (Figure 3) to be used for drying food grains is shown in Figure 2. The burner types were the KNUST Biomass Burner (KBB) and the AflaSTOP Biomass Burner (ABB). They were fabricated at the Workshop of the Department of Agricultural and Biosystems Engineering at Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. In addition to the biomass burners, a cylindrical column that acts as the drying chamber was also fabricated at the same workshop.

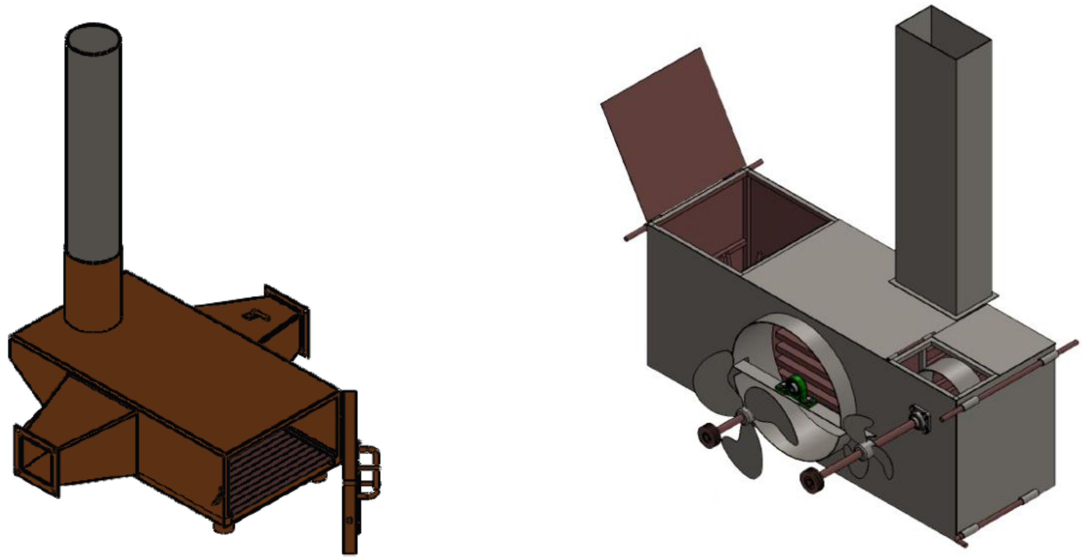
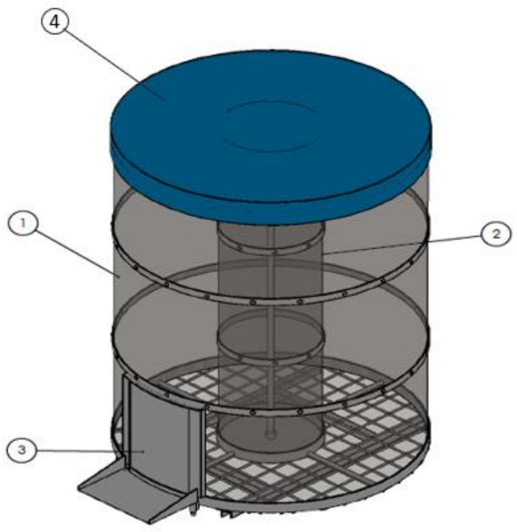


Figure 2. KNUST-ABE Biomass Burner (left) and AFLASTOP Biomass Burner (right)



Part No	Part name
1	Outer cylindrical bin
2	Inner bin forming the plenum
3	Discharge gate
4	Tarpaulin for covering system during drying

Figure 3. Column dryer showing parts

2.2.2. Technical assessment of the portable biomass burners

The technical performance of two portable biomass burners were assessed for the study. This was done to quantify the efficiency of the burner systems which served as a basis for applying the AHP appropriately. One kilogram of corncobs was weighed and fed into the combustion chamber of the two portable biomass burners considered in the study, and the time taken for the corncobs to combust completely was taken note. During the combustion, an Amprobe TMD-50 Thermocouple K-type thermometer (Amprobe Instrument Corporation, Everett, USA) was used to record the temperature variations both in the combustion chamber and the processed air to be used for drying. In addition to that, the velocity of the heated air, thus, processed air to be used for drying, was also recorded with a thermo-anemometer (Extech, Melrose, MA, USA). Equations 1 to 4 were used in the determination of biomass efficiency.

$$M_{air} = V_{air} \times \rho_{air} \quad (1)$$

$$Q_a = M_{bc} \times H_V \quad (2)$$

$$Q_s = M_{air} \times C_{Pair} \times (T_{air} - T_{amb}) \quad (3)$$

$$Burner_{eff} = \frac{\text{Heat supplied (Qs)}}{\text{Heat available (Qa)}} \times 100 \quad (4)$$

Where: V_{air} = volumetric flow rate (m^3/s), ρ_{air} = density of air (kg/m^3), M_{air}= mass flow of air (kg/hr), T_{air}= temperature of hot air exiting the heat exchanger (˚C), T_{amb}= temperature of ambient (˚C), C_{Pair}= specific heat capacity of air (kJ/kg. ˚C), H_V=Heat value of corncobs (kJ/kg) and M_{bc}=feed rate of biomass (kg/hr).

3. Results and discussion

3.1. Technical performance of the portable biomass burner systems

Overall, the KBB had a higher burner efficiency of 45 % while the ABB performed at an efficiency of about 20 %. The consumption of fuel (corn cobs for this case) was least in the KBB as compared to the ABB. Although the capacity of the combustion chamber of the ABB is bigger than the KBB making the ABB have a bigger space to utilize more biomass, the rate of heat loss in the ABB is high unlike the KBB which has a compact combustion chamber. The compactness does not allow the KBB to lose heat at a faster rate compared to the ABB. The high heat loss associated with the ABB results in its high consumption of biomass to give the same output temperature. 12 kg of corn cobs combusted per hour in the KBB gave rise to an outlet temperature of 100 ˚C as compared to 24 k of corn cobs combusted per hour in the ABB, giving rise to an output temperature of 92 ˚C. Thus, the ABB consumes double the amount of biomass consumed by the KBB to give almost the same output temperature.

3.2. Application of AHP in the selection of the Appropriate Biomass Burner

3.2.1. Priority weight of criteria

Comparison between all criteria in pairs using the scale in Table 1 is shown in Table 3. The weight of each criterion was based on technological knowledge and general engineering theories with the focus on the main objective, which was to select an appropriate burner system. Several researchers in different fields of engineering studies have applied these in some applicable studies (Bena & Fuller, 2000; Chasapis *et al*., 2008; Tarigan & Tekasakul, 2005) in. For instance, in the selection of a biomass burner, the efficiency of the burner (which considers the energy consumption by the system, the effectiveness of heat exchangers incorporated in it and the maximum airflow at a specific pressure) is obviously more important than the ease of use of the burner (Hou *et al*., 2011). In this instance, considering the scale from Table 1, a score of 5 is given for the comparison between C1 and C2. Following the AHP procedure in creating the pairwise comparison matrix, if C1 is 5 times more preferred to C2, then C2 is 1/5 times more preferred to C1. By comparing a criterion by itself, the score is 1 and, this is the reason why the value, 1 is recorded on the matrix's diagonal (Constantin 2010; Darko *et al*., 2019).

Table 3. Pairwise comparison matrix of criteria for selecting a biomass burner

Criteria for selection	C1	C2	C3	C4	C5	C6	C7
C1	1.00	5.00	1.00	3.00	9.00	9.00	9.00
C2	0.20	1.00	0.14	0.14	3.00	5.00	5.00
C3	0.33	7.00	1.00	0.33	7.00	7.00	7.00
C4	0.33	7.00	3.00	1.00	7.00	7.00	7.00
C5	0.11	0.33	0.14	0.14	1.00	0.50	1.00
C6	0.11	0.20	0.14	0.14	2.00	1.00	0.50
C7	0.11	0.20	0.14	0.14	1.00	2.00	1.00

C1 = Burner efficiency; C2 = Ease of use; C3 = Cost of manufacture; C4 = Durability; C5 = Mobility; C6 = Manufacturability and C7 = Versatility

Table 3 was normalized to a scale of 1, and its values in each row was averaged to give the weight of each criterion considered for the selection process. This is shown in Table 4. The radar plot in Figure 4 shows the average values from Table 4, and in its representation, it shows that the selection of a biomass burner, the burner efficiency is of utmost importance since it had a relative weight of 0.34 out of 1. This is followed by the durability, cost of manufacture, ease of use, versatility, manufacturability, and mobility of the burner system with relative weights of 0.27, 0.20, 0.09, 0.03, 0.03 and 0.03 out of 1, respectively.

In the selection of an appropriate biomass burner system, efficiency becomes an essential factor that must be considered (Panwar *et al*., 2011). The efficiency of a burner directly influences the overall performance of a drying system which is the drying efficiency. An efficient biomass burner consumes less fuel (biomass) to heat drying air to a required temperature. In this way, the energy consumption of a drying system can be directly associated with the efficiency of the burner heat source attached to the drying system, the higher the burner efficiency, the lower the energy consumption and vice versa. Moreover, studies by (Jorge *et al.*, 2015) indicated that energy consumption accounts for 54% of the total cost of running a drying system. This means that selecting an efficient biomass burner as a dryer heat source contributes to a lower dryer operational cost as compared to a less efficient biomass burner. This presents an interesting consideration by smallholder farmers in Ghana and many other sub-Sahara African countries in the utilization of low-cost drying systems.

Table 4. Normalized form of decision criteria matrix

Criteria for Selection	C1	C2	C3	C4	C5	C6	C7	Priority weights
C1	0.45	0.24	0.18	0.61	0.30	0.29	0.30	0.34
C2	0.09	0.05	0.03	0.03	0.10	0.16	0.16	0.09
C3	0.15	0.34	0.18	0.07	0.23	0.22	0.23	0.20
C4	0.15	0.34	0.54	0.20	0.23	0.22	0.23	0.27
C5	0.05	0.02	0.03	0.03	0.03	0.02	0.03	0.03
C6	0.05	0.01	0.03	0.03	0.07	0.03	0.02	0.03
C7	0.05	0.01	0.03	0.03	0.03	0.06	0.03	0.03
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

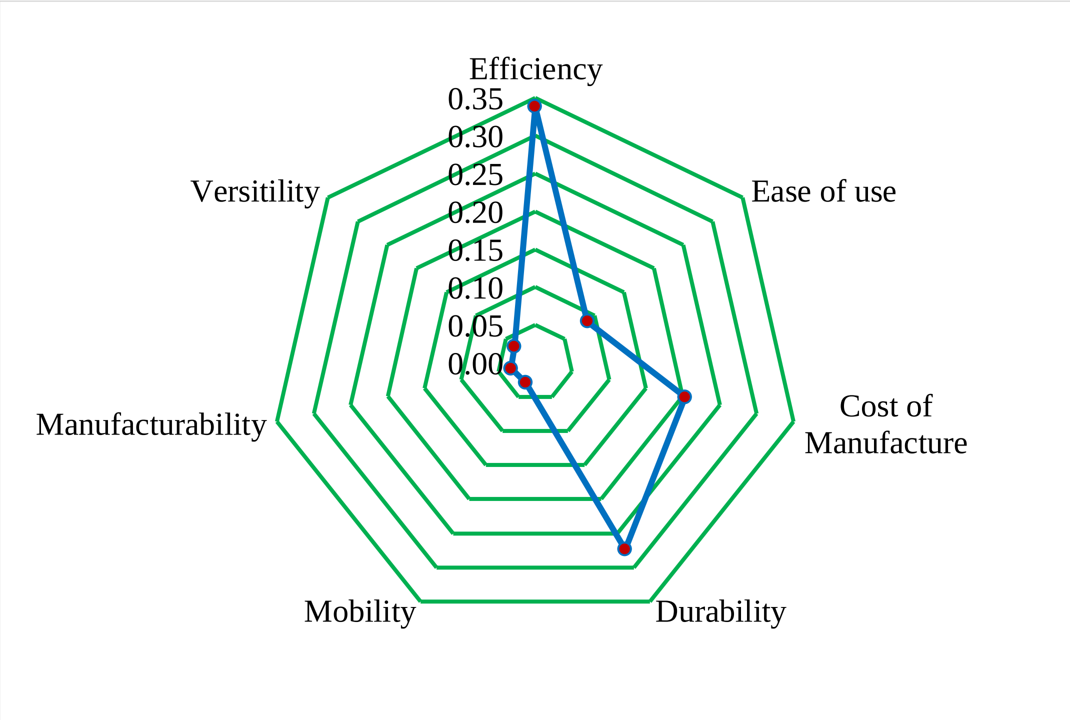


Figure 4. Overall priorities of criteria in the selection of an appropriate potable biomass burner

Durability and manufacturing cost had relatively high priority scores in the selection of a biomass burner system to be used by smallholder farmers in the Ghanaian context. Farmers would want a system that can last long and usually at a lower cost. A system that is robust and shows resilience to wear and damage from one drying season to the next is what must be considered for selection. The durability of the burner system may come from the choice of manufacturing material and from the configuration of various parts of the system, the fabrication of joints, and the location of certain critical stress-prone parts. The other criteria are all considered appropriate in the process of selecting various components of a drying system and as such, have their relative importance as highlighted in this study.

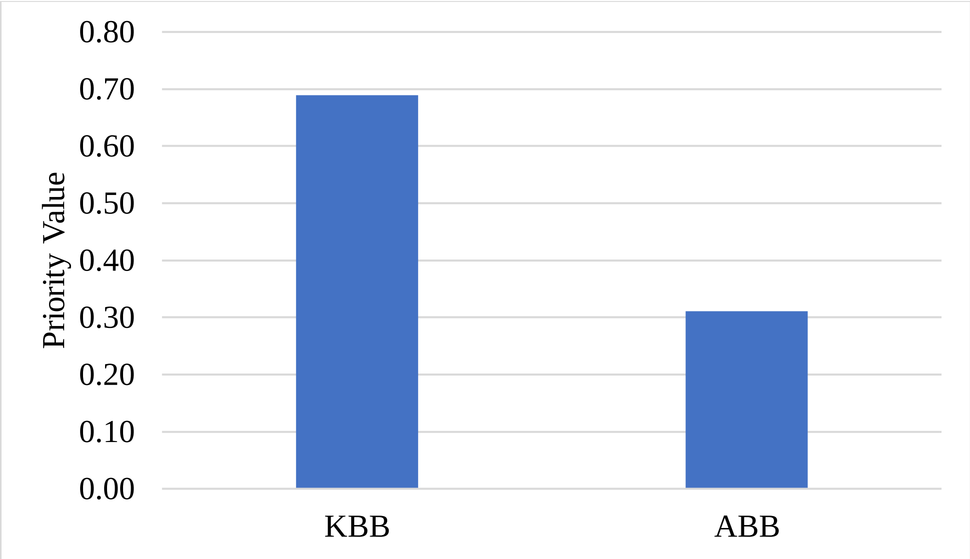


Figure 5. Model synthesis for the selection of the appropriate biomass burner

It is worth pointing out that the priority values are not given randomly but were derived based on judgmental preference and backed by results from experimental and technical information. More so, the priority weights derived in Figure 4 have mathematical validity, and as such, can be interpreted intuitively. Burner efficiency scored 34% of the criteria's overall importance, followed by durability at 27%, cost (20%) and similar scores observed for the other parameters.

3.2.2. Consistency of judgmental priority matrix

Due to the human aspect of taking decisions based on scales, it was worth checking for the consistency in the scores given to each comparison. This step has been developed in the AHP process to ensure that consistent score are given to each comparison stage (Alonso & Lamata, 2006). With the seven criteria considered in the study, a value of 1.342 was selected as the Random Index (Brunelli, 2015). The maximum eigenvalue for the decision criteria matrix was calculated to be 7.7, resulting in a Consistency Index of 0.11. Finally, a Consistency Ratio (CR) of 0.086 was determined. Priority matrix was considered sufficient as the criteria for the study were clearly defined (Barati *et al*., 2019). Similar evidence in studies that focused on the selection of appropriate drying platform for maize drying in a solar bubble dryer, selection of appropriate dryer for drying tomatoes, and choosing of an optimal water distribution system have been reported (Armah *et al*., 2021; Aşchilean *et al*., 2017; Hruška, *et al*., 2014; Jorge *et al*., 2015).

3.2.3. Preferences for the alternatives

The relative weight of the biomass burner alternatives based on each criterion was analyzed in the same way as developing the priority weight for the criteria matrix. The biomass burner alternatives were compared to each other per each of the sub-criterion considered in the study; followed by normalizing the relative weight between the biomass burner alternatives according to each of the criteria to get the performance matrix of the two biomass burner alternatives in relation to the seven decision criteria, as shown in Table 5. It is not easy to come up with the better alternative out of the two since each of the two biomass burner alternatives performs differently under each criterion (Chewaphorn & Kasin, 2020). For instance, when it comes to burner efficiency KBB, which had a weight of 0.83 performed better than the ABB with a weight of 0.17. However, ABB has a better performance in terms of cost of manufacture as compared to KBB.

Table 5. Preferences for alternatives with respect to each criterion

Criteria	KBB	ABB
Burner Efficiency	0.83	0.17
Ease of use	0.88	0.13
Cost of manufacture	0.13	0.88
Durability	0.88	0.13
Mobility	0.25	0.75
Manufacturability	0.13	0.88
Versatility	0.83	0.17

In that regard, the final step in the AHP which results in the development of the overall priority of each of the biomass burners is shown in Figure 5. It can be noticed that the KBB had a priority value of 0.69 while the ABB had a value of 0.31. Given the judgmental importance of each criterion considered in the selection process, the KBB is preferable compared to the ABB.

4. Conclusion

To address the obvious challenges associated with post-harvest loss in sub-Saharan Africa, many researchers, technologists, and practitioners in the field have been innovative in the introduction of technologies for possible adoption. Decisions in the selection of an appropriate technology to be utilized by farmers are significant and could form the basis for the possible adoption of such technologies. AHP has been applied in this study to select a portable biomass burner to be integrated into a crossflow column drying system in this study. Based on a global priority index of 0.69, the KNUST-ABE Biomass Burner was selected over the AFLASTOP Biomass Burner which had a global priority index of 0.31. From the study, it is shown that the criteria, sub-criteria, and proper application of the AHP tool are suitable for the selection process, and hence, provided a satisfactory result as expected.

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