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Sustainable Raw Material Selection For Pulp and Paper Using SAW Multiple Criteria Decision Making Design.

ABSRACT

Identification of suitable specie and determination of suitable age of a tree are two important aspects related to selection of raw material for wood based pulp and paper industry. General procedure adopted for addressing these problems includes the following steps: physicochemical characterization of raw material, morphological analysis of raw material, performing designed pulping and bleaching experiments, evaluation of pulp characteristics and mechanical strength properties of paper sheets. This study attempts to make these raw material selection efforts shorter and simpler using simple additive weighting (SAW) multiple criteria decision making (MCDM) approach taking into account only the proximate-chemical, physical and morphological features of raw materials. A total of four case studies related to selection of suitable specie of Eucalyptus and Leucaena; and selection of suitable age of Acacia and Leucaena species have been presented to demonstrate and validate the methodology of the proposed process. SAW method has been applied to the decision making unit comprising proximate-chemical, physical and morphological characteristics of these raw materials to rank them according to preference for pulping and papermaking. Results achieved in this research are in confirmation of those published in literature and reveal that the SAW method is practical, feasible, and simple to apply for pulp and paper based raw material selection.

Keywords: Raw Material, Physicochemical Analysis, Morphological Features, SAW Method, Decision making, Sustainability

INTRODUCTION

A strategy and a procedure to identify, select and introduce a raw material are extremely decisive for pulp and paper industry since determining a raw material for pulp and paper production helps in (i) developing crop management and storage methods for the selected species; (ii) promoting crop variety and harvesting research, (iii) establishing cooking and bleaching methods; (iv) shaping chemical recycling, environmental advantages and paper quality; and eventually (v) optimizing logistics and economic benefits [1]. Further at the time, when the supply of wood is badly hitting a total 31% wood based Indian paper mills and they have to depend on social and farm forestry plantations for meeting the wood demand [2], a simple and feasible strategy to identify, select and introduce a tree crop can be highly helpful in light of above advantages. Generally, two common types of selections are made for wood based raw material for pulp and paper, one, selection of specie of a tree and, another, selection of age of particular specie of a tree. The general course of actions implemented for making such selections include the following basic steps: proximate chemical characterization of raw material, morphological analysis of raw material, performing designed pulping and bleaching experiments, evaluation of pulp characteristics and mechanical strength properties of paper sheets. Implementing these steps consume a great quantity of time, manpower and chemicals. We sought to make this raw material selection process shorter, simpler and easier taking into account only proximate-chemical, physical and morphological features of wood. Earlier, we suggested application of multiple criteria decision making (MCDM) approach using technique for order preference by similarity to ideal solution (TOPSIS) in selection of suitable raw material for pulping and papermaking [3]. This method was found practically easy to apply and the results obtained match those reported in the literature. The present work extends that study with the view to make selection process further simpler and quicker using the simple additive weighted (SAW) method under MCDM.

LITERATURE REVIEW

Several researchers have highlighted the raw material selection problem related to the specie and age in their publications. Khristova et al. [4] examined four Eucalypts species viz. Eucalyptus camaldulensis, Eucalyptus citriodora, Eucalyptus microtheca and Eucalyptus tereticornis and found Eucalyptus citriodora the best alternative for pulp and paper production. Selection of suitable Leucaena species for pulping has been reported in the literature through series of publications [5-7]. In these works, researchers have undertaken five varieties of the Leucaena namely Leucaena diversifolia, Leucaena collinsii, Leucaena leucocephala (India), Leucaena leucocephala (Honduras) and Leucaena leucocephala (K360). These associates found Leucaena diversifolia the best raw material for pulp production. Chang et al. [8] investigated the stems of 0.2, 1.2 and 3-year-old Bambusa stenostachya for pulping and papermaking and they came to the conclusion that the bamboo stems only younger than 1-year-old should be used for pulping and papermaking. López et al. [5] attempted to select the best wood raw materials for cellulose pulp and papermaking among Leucaena diversifolia with different growth periods of one, two and three years. Their studies revealed that Leucaena diversifolia in its second year of growth was the most suitable material for pulp and papermaking. Wang et al. [9] tried to select suitable vertical locations (root, middle and top) in Korean spruce with different age groups for pulp and paper; and they found the middle part of the log of 32 years old Korean spruce to exhibit better pulping characteristics. In all these efforts, the general courses of actions as mentioned above were taken. We are trying to explore the possibilities and efficacy of MCDM methods to deal with such aforementioned raw material selection problems in pulp and paper industry.

It is important to mention here that MCDM methods have been used for solving forest resource management problems over the last three decades [10] but the application of these methods are rare in pulp and paper sector although this sector depends primarily on forest resources. MCDM comes under the operation research which refers to making decision in the presence of multiple, numerous and usually conflicting criteria and provides a step by step modus operandi for which a compromise decision can be reached at by a group of decision makers [11]. Among several MCDM methods, SAW is the simplest, natural and most widely used multicriteria evaluation methods [12]. Abdullah and Adawiyah [11] presented a decade review on SAW methods highlighting the various applications related to successful selection of different materials and processes. However, there is no SAW application yet for the selection of raw material for pulp and paper. With the view that application of MCDM methods are rare in selection of raw material for pulp and paper; and SAW technique being the simplest among them has never been utilized for this purpose, this investigation endeavours to undertake these raw material selection problems employing SAW multiple criteria decision making approach only on the basis of proximate-chemical and morphological features of raw materials to make the selection process easier, shorter and more simple. Fig. 1 illustrates the proposed SAW framework for raw material selection of pulp and paper production.

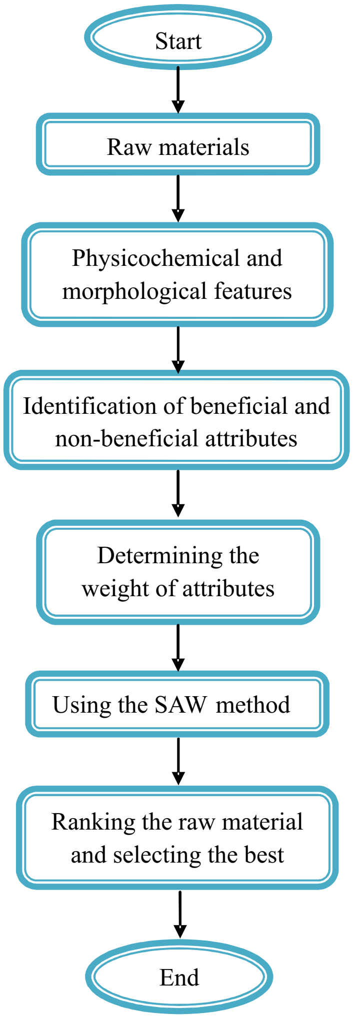


Fig. 1 Proposed SAW method for Pulp and Paper raw material selection

DESCRIPTION OF METHODS ADOPTED

Beneficial and Non-beneficial Attributes

During the selection of a suitable alternative according to MCDM methods, the decision makers have to consider all the attributes or characteristics of available alternatives. Hence, identification of beneficial and non-beneficial attributes among various attributes affecting the selection is crucial. The beneficial attributes refer to those features or characteristics which provide an upper hand towards the process or material; while the non-beneficial attributes mean those characteristics which contribute towards disadvantages of process or material. Hence, for beneficial and non-beneficial attributes higher and lower values are always preferable respectively.

Selection of a raw material for pulp and paper depends upon their different proximate-chemical, physical and morphological attributes. The attributes considered in this work are ash percentage (AP); hot-water solubility (HW); cold-water solubility (CW), NaOH solubility (NS); alcohol benzene extractives (EX); holocellulose (HC); lignin (LG); alpha cellulose (AC); fiber length (FL); cellulose (CL), pentosans (PS) and basic density (BD). Anupam et al. [3] classified AP, HW, NS, EX, LG as non-beneficial attributes while HC, AC, FL, CL and PS as beneficial attributes since the lower values of former and higher values of later are advantageous for pulping and papermaking. Two more attributes CW and BD are introduced in this study. Since, the water solubility in the raw material lowers the pulp yield, the CW can be considered as non-beneficial attribute and hence its lower values are desired. Further, efficient production of pulp can be achieved with wood having reasonably high wood density as it influences the process economics and specific wood consumption strongly [13]. Hence, a higher value of basic density of wood is desired and thus it can be considered as beneficial attribute.

SAW Method

SAW method is also known as weighted linear combination or scoring methods or weighted sum method. This method demonstrates the main concept of MCDM for the integration of the criteria values and weights into a single magnitude [12]. In this method a composite performance score is determined for each alternative by multiplying the normalized value assigned to the attributes of that alternative with their weights of comparative importance evaluated by decision maker followed by adding of the products for all criteria. The advantage of SAW is that it is a proportional linear transformation of the raw data which means that the relative order of magnitude of the standardized scores remains equal [14]. Procedure to decide the best alternative through SAW includes the steps as described below:

Step 1: Establishment of a decision matrix. An array of alternatives, attributes and performance values of alternatives under attributes is called the decision matrix. A selection problem having A_i(i=1,2,3,......m) alternative candidates; C_j (j =1,2,3,......m) attributes or criteria; a_{ij}(i =1,2,3,......m; j =1,2,3,......m) performance values of attributes can be represented in the form of decision matrix $DM(a_{ij})_{mxn}$ as shown below:

$$DM(a_{ij})_{mxn}$$

$$= \begin{array}{cccccc} & C_1 & C_2 & C_3 & - & C_j \\ A_1 & a_{11} & a_{12} & a_{13} & - & a_{1j} \\ A_2 & a_{21} & a_{22} & a_{23} & - & a_{2j} \\ A_3 & a_{31} & a_{32} & a_{33} & - & a_{3j} \\ - & - & - & - & - & - \\ A_j & a_{1j} & a_{2j} & a_{3j} & - & a_{ij} \end{array}, \quad i=1,2,3,......m; j=1,2,3,......m \qquad (1)$$

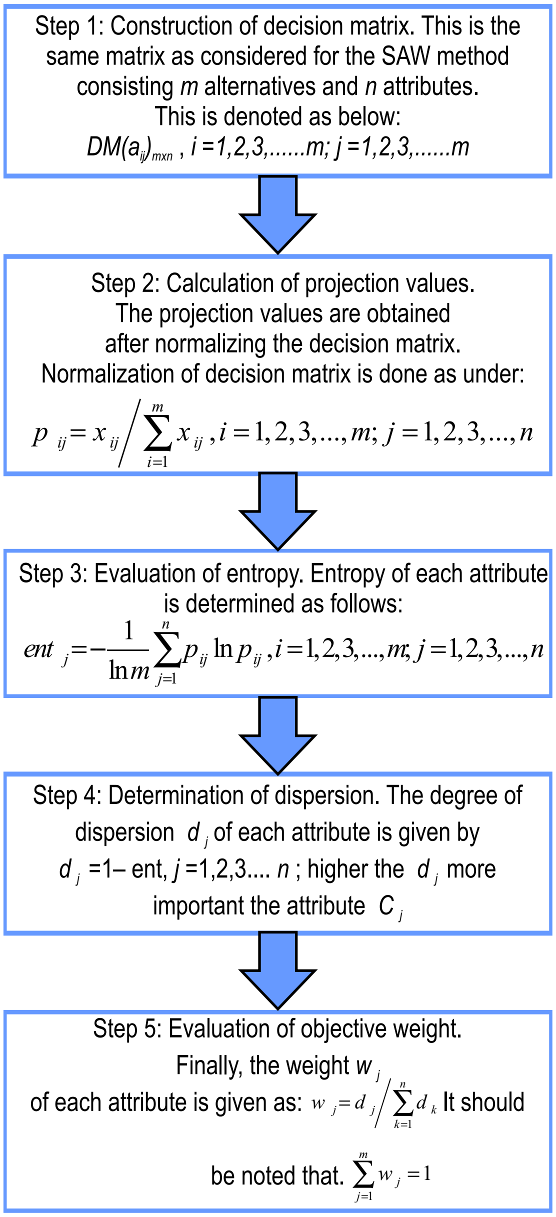
Step 2: Normalization of the decision matrix: Normalization of every attribute in the decision matrix is done to convert the attributes to dimensionless values in order to ensure the compatibility between absolute and comparative justification on the one hand and between quantitative and qualitative judgement on the other hand [15]. Normalizing the attributes in decision matrix is done on the basis of values of non-beneficial and beneficial attribute. The normalized values $(a_{ij})_{normalized}$ for non-beneficial and beneficial attributes are calculated by Eq. (2) and (3) respectively as shown below:

$$(a_{ij})_{normalized} = \frac{\min\limits_{j} a_{ij}}{a_{ij}} \qquad (2)$$

$$(a_{ij})_{normalized} = \frac{a_{ij}}{\max\limits_{j} a_{ij}} \qquad (3)$$

Here, $\min\limits_{j} a_{ij}$ represents the lowest value of non-beneficial attribute and $\max\limits_{j} a_{ij}$ is the highest value of beneficial attribute. For the non -beneficial attribute the smallest value is the best while for the beneficial attribute the largest value is the best. Thus, the best criterion value (i.e. the largest one for a maximizing criterion and the smallest one for a minimizing criterion) gets the largest value equal to unity [16].

Step 3: Determination of the weight of the attributes: Weights to criteria play an important role for measuring overall preferences of alternatives [17]. Determination of weight of an attribute refers to calculation of the relative quantitative importance of a particular attribute with respect to the objective. Several methods such as standard deviation method, entropy method, AHP method etc. have been reported in literature to calculate the weights of attributes. In this investigation, entropy method has been used to calculate the objective weights. Fig. 2 represents the stepwise procedure for implementing the entropy method [3].



Step 1: Construction of decision matrix. This is the same matrix as considered for the SAW method consisting *m* alternatives and *n* attributes. This is denoted as below:

$DM(a_{ij})_{mxn}$, $i = 1,2,3,......m; j = 1,2,3,......m$

Step 2: Calculation of projection values. The projection values are obtained after normalizing the decision matrix. Normalization of decision matrix is done as under:

$$p_{ij} = x_{ij} \Big/ \sum_{i=1}^{m} x_{ij} , i = 1,2,3,...,m; j = 1,2,3,...,n$$

Step 3: Evaluation of entropy. Entropy of each attribute is determined as follows:

$$ent_j = -\frac{1}{\ln m} \sum_{j=1}^{n} p_{ij} \ln p_{ij} , i = 1,2,3,...,m; j = 1,2,3,...,n$$

Step 4: Determination of dispersion. The degree of dispersion d_j of each attribute is given by $d_j = 1 - ent, j = 1,2,3.... n$; higher the d_j more important the attribute C_j

Step 5: Evaluation of objective weight. Finally, the weight w_j of each attribute is given as: $w_j = d_j \Big/ \sum_{k=1}^{n} d_k$ It should be noted that. $\sum_{j=1}^{m} w_j = 1$

Fig. 2 Steps to calculate weights by entropy method

Step 4: Calculation of composite performance score: The overall or composite performance score of an alternative is calculated as follows:

$$S_i = \sum_{j=1}^{n} w_j \left(a_{ij}\right)_{normalized} , i = 1,2,3,..... m; (4)$$

Step 5: Ranking of alternatives: Depending on the composite performance score computed in step 4, the candidate alternatives are organized in the descending order with the most appropriate candidate taking the first place and the least appropriate candidate taking the last place.

CASE STUDIES FOR RAW MATERIAL SELECTION

Four case studies related to selection of Eucalyptus species, selection of Leucaena species, selection of age of Leucaena diversifolia sprouts and selection of age of Acacia crassicarpa trees have been formulated on the basis of proximate-chemical, physical and morphological properties published in the literature and obtained through experiments to demonstrate and validate the suitability of SAW method application in raw material selection for pulp and paper production.

Case 1: Selection and Ranking of Eucalyptus Species

Three same age species of Eucalyptus namely E. citriodora, E. camaldulensis and E. microtheca have been considered in this case. The decision matrix consisting of proximate chemical properties of these three Eucalyptus species as presented by Khristova et al. [4] has been demonstrated in Table 1. The attributes considered in the decision matrix are AP, HW, NS, EB, CL, PS and LG where AP, HW, NS, EX

Table - 1

SAW method for selection of Eucalyptus species

Decision matrix for different Eucalyptus species

Eucalyptus species	AP	HW	NS	EX	CL	PS	LG
E. camaldulensis (E1)	0.7	5.2	15.5	4.1	44.1	18.7	20.0
E. citriodora (E2)	0.8	3.7	15.8	3.6	48.2	19.1	22.7
E. microtheca (E3)	0.7	7.0	15.8	4.8	42.3	18.1	20.7

Normalized decision matrix for different Eucalyptus species

Eucalyptus species	AP	HW	NS	EX	CL	PS	LG
E. camaldulensis (E1)	1	0.7115	1	0.8780	0.9149	0.9791	1
E. citriodora (E2)	0.875	1	0.9810	1	1	1	0.8811
E. microtheca (E3)	1	0.5286	0.9810	0.75	0.8776	0.9476	0.9662

Weight of the attributes for different Eucalyptus species

Attribute	AP	HW	NS	EX	CL	PS	LG
Weight	0.0459	0.7174	0.0048	0.1546	0.0338	0.0072	0.0362

Ranking of different Eucalyptus species

Eucalyptus species	Composite Score	Rank using SAW	Rank using experiments
E. camaldulensis (E1)	0.7710	2	2
E. citriodora (E2)	1.825	1	1
E. microtheca (E3)	0.6172	3	3

Table - 2

SAW method for selection of Leucaena species

Decision matrix for different Leucaena species

Leucaena species	FL	HW	NS	EX
L. diversifolia (L1)	0.822	2.66	15.92	3.75
L. collinsii (L2)	0.680	3.18	21.89	5.79
L. leucocephala (L3)	0.920	2.50	17.88	5.84

Normalized decision matrix for different Leucaena species

Leucaena species	FL	HW	NS	EX
L. diversifolia (L1)	0.8935	0.9398	1	1
L. collinsii (L2)	0.7391	0.7862	0.7273	0.6477
L. leucocephala (L3)	1	1	0.8904	0.6421

Weight of the attributes for different Leucaena species

Attribute	FL	HW	NS	EX
Weight	0.1867	0.1333	0.2160	0.4640

Ranking of different Leucaena species

Leucaena species	Composite Score	Rank using SAW	Rank using experiments
L. diversifolia (L1)	0.9721	1	1
L. collinsii (L2)	0.7004	3	3
L. leucocephala (L3)	0.8103	2	2

and LG are non-beneficial while CL and PS are beneficial. The weights of different attributes calculated using steps shown in Fig. 2 have been put in Table 1. The normalized decision matrix, and composite score of different Eucalyptus species calculated using Eqs. (2), (3) and (4) respectively are also shown in Table 1. It can be observed from Table 1 that E. citriodora has the highest overall score among all the Eucalyptus species and hence can be considered as the most suitable for pulp production.

Table - 3

SAW method for selection of Leucaena diversifolia sprouts of different age

Decision matrix for Leucaena diversifolia sprouts of different age

Leucaena diversifolia sprouts	HW	NS	EX	HC	LG	AC
First year sprout (P1)	0.71	2.73	1.90	94.5	1.74	81.4
Second year sprout (P2)	1.04	1.63	0.65	94.5	1.37	79.9
Third year sprout (P3)	0.98	2.47	0.30	92.9	5.70	77.2

Normalized decision matrix for Leucaena diversifolia sprouts of different age

Leucaena diversifolia sprouts	HW	NS	EX	HC	LG	AC
First year sprout (P1)	1	0.5971	0.1579	1	0.7874	1
Second year sprout (P2)	0.6827	1	0.4615	1	1	0.9816
Third year sprout (P3)	0.7245	0.6599	1	0.9831	0.2404	0.9484

Weight of the attributes for Leucaena diversifolia sprouts of different age

Attribute	HW	NS	EX	HC	LG	AC
Weight	0.0902	0.0423	0.4775	0.0002	0.3894	0.0004

Ranking of different Leucaena diversifolia sprouts of different age

Leucaena diversifolia sprouts	Composite Score	Rank using SAW	Rank using experiment
First year sprout (P1)	0.4981	3	3
Second year sprout (P2)	0.7142	1	1
Third year sprout (P3)	0.6650	2	2

Table - 4

SAW method for selection of Acacia crassicarpa trees of different age

Decision matrix for Acacia crassicarpa trees of different age

Acacia crassicarpa trees	AC	BD	AP	LG	HC	HW	CW	PS	NS	EX
Fourth year tree (T1)	35.96	400	0.27	30.92	77.02	3.11	0.13	13.56	19.21	2.47
Fifth year tree (T2)	37.87	435	0.28	31.25	75.43	2.15	0.25	13.58	22.51	3.97
Sixth year tree (T3)	39.68	465	0.16	31.10	78.52	2.46	0.49	12.9	17.69	4.66

Normalized decision matrix for Acacia crassicarpa trees of different age

Acacia crassicarpa trees	AC	BD	AP	LG	HC	HW	CW	PS	NS	EX
Fourth year tree (T1)	0.9063	0.8602	0.5926	1	0.9809	0.6913	1	0.9985	0.9209	1
Fifth year tree (T2)	0.9544	0.9355	0.5714	0.9894	0.9606	1	0.52	1	0.7859	0.6222
Sixth year tree (T3)	1	1	1	0.9942	1	0.8740	0.2653	0.9499	1	0.5300

Weight of the attributes for Acacia crassicarpa trees of different age

Attribute	AC	BD	AP	LG	HC	HW	CW	PS	NS	EX
Weight	0.0034	0.0053	0.1235	0.0005	0.0029	0.0524	0.5819	0.0014	0.0879	0.1408

Ranking of Acacia crassicarpa trees of different age

Acacia crassicarpa trees	Composite Score	Rank using SAW	Rank using experiments
Fourth year tree (T1)	0.9254	1	1
Fifth year tree (T2)	0.5951	2	2
Sixth year tree (T3)	0.4996	3	3

These species can now be arranged in descending order of their preferences for pulp production as E. citriodora (E2) > E. camaldulensis (E1) > E. microtheca (E3). It is interesting to mention here that the results and ranking order achieved using entropy based SAW approach exactly tally with those predicted by Khristova et al. [4] through experiments and by Anupam et al. [3] through TOPSIS.

Case 2: Selection and ranking of Leucaena species

Three Leucaena species viz. L. diversifolia, L. collinsii and L. leucocephala have been chosen for this case study. The decision matrix comprising of morphological and chemical properties of second year L. diversifolia, L. collinsii and L. leucocephala (India) varieties as presented by Díaz et al. [6] has been shown in Table 2. This decision matrix consists of FL as beneficial attribute while HW, NS and EX as non-beneficial attributes. The weights of FL, HW, NS, and EX as calculated using steps shown in Fig. 2 have been given in Table 2. The normalized decision matrix, and composite score of different Leucaena species calculated using Eqs. (2), (3) and (4) respectively are also demonstrated in Table 2. It can be seen from Table 2 that L. diversifolia has the highest composite score among all the Leucaena species and hence can be considered as the most suitable for pulp production. These species can now be arranged in descending order of their preferences for pulp production as L. diversifolia (L1) > L. leucocephala (L3) > L. collinsii (L2). It should be highlighted here that the results and ranking order achieved for Leucaena species using entropy based SAW approach exactly match with the experimental findings mentioned in the literature [6] as well as those reported by us in a previous study [3].

Case 3: Selection and ranking of Leucaena diversifolia sprouts of different age

This case takes the selection and ranking of Leucaena diversifolia with growth periods of one, two and three years. The decision matrix including proximate chemical properties of Leucaena diversifolia pulps as presented by López et al. [5] has been shown in Table 3. HW, NS, EX and LG are the non-beneficial attributes while HC and AC are the beneficial attributes considered in this case. The weights of HW, NS, EX, LG, HC and AC as calculated using steps shown in Fig. 2 have been given in Table 3. The normalized decision matrix, and composite score of different Leucaena diversifolia sprouts calculated using Eqs. (2), (3) and (4) respectively are also demonstrated in Table 3. It can be manifested from Table 3 that the pulp obtained from second year sprout has the highest composite score of all the L. Diversifolia pulps and hence can be believed as the most suitable pulp for papermaking. These pulps can be arranged in descending order of their preferences for paper production as: Second year sprout (P2) ▯ Third year sprout (P3) ▯ First year sprout (P1). Though rankings for these sprouts are not provided, yet it is important to mention that the most suitable pulp selected for papermaking using SAW approach exactly matches with that predicted by López et al. [5]. However, these ranking are strictly in order as estimated by us previously using TOPSIS method [3].

Case 4: Selection and ranking of Acacia crassicarpa trees of different age

Selection and ranking of Acacia crassicarpa trees with growth periods of four, five and six years have been taken in this case. The decision matrix shown in Table 4 shows proximate-chemical and physical properties determined in this case as per international standards: AC (TAPPI T 203 om-88), AP (TAPPI T 244 cm-99), LG (TAPPI T 222 om-02), HC (TAPPI T 249 cm-00), HW, CW (TAPPI T 207 cm-99), PS (UV Method), NS (TAPPI T 212 om-02), EX (TAPPI T 204 cm-97) and BD (SCAN-CM 43:95). Laboratory scale Kraft pulping of Acacia crassicarpa 4, 5 and 6 year wood chips with target kappa number 15 were performed respectively at: 19%, 18%, 18% Na_2O; cooking temperatures 166 °C and time to reach cooking temperature 90 min. The unbleached pulp was put for oxygen delignification followed by $DEpD_1D_2$ bleaching sequence to achieve final brightness 89 ± 1% ISO. It was found that Acacia crassicarpa of harvesting age 4 years was the best in terms of brightness (88.8%), chemical demand, and strength properties of bleached pulp (bulk 1.15 cm^3/g, breaking length 8.163 km, tensile index 83.80 Nm/g, tear index 6.25 mNm^2/g) while Acacia crassicarpa of harvesting age 5 and 6 years occupy the second and third position respectively. The same problem was approached through application of SAW method. The weights of non-beneficial (AP, HW, CW, NS, EX, LG) and beneficial (BD, HC, AC) attributes as calculated using steps shown in Fig. 2 have been given in Table 4. The normalized decision matrix, and composite score of different Acacia crassicarpa trees calculated using Eqs. (2), (3) and (4) respectively are also presented in Table 4. It can also be noticed from Table 4 that Acacia crassicarpa of harvesting age 4 has the highest composite score of all the Acacia crassicarpa trees while other follows the same experimental sequence. Thus, the prediction of the best harvesting age of Acacia crassicarpa as well as their ranking exactly matches the results as obtained through time, chemical and manpower consuming experiments.

CONCLUSION

This research has proposed an MCDM framework based on entropy integrated SAW method for selection and ranking of suitable raw material for pulping and papermaking process. The introduced framework has been satisfactorily tested on the four cases related to selection of suitable specie of Eucalyptus and Leucaena; and selection of suitable age of Acacia and Leucaena species. The decision matrix has been chosen from the well-established investigation reported in the literature and experiments carried out in laboratory. The decision matrix consisted of proximate-chemical, physical and morphological properties of raw materials such as ash percentage; hot-water solubility; cold-water solubility, NaOH solubility; alcohol benzene extractives; holocellulose; lignin; alpha cellulose; fiber length; cellulose, pentosans and basic density. The results obtained in this study have been validated using those described in the literature as well as found during experiments and it is stimulating to observe the similarity. Hence, it can be concluded that the suggested decision support methodology is effective in identifying, selecting and introducing a suitable pulping and papermaking woody raw material. However, incorporating other raw material attributes such as cost, availability, harvesting techniques, growth rate, climatic adaptations etc. in the decision matrix and developing SAW method in a fuzzy environment can be contemplated as a further research subject for improving and facilitating the decision support system for pulp and paper raw material selection. With these efforts, better and quicker decisions can be taken about which tree species of what age to focus in sustainable forestry programs to increase the mill profitability.

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