ASSESSMENT OF FIVE SUCCESSFUL POPLAR CLONES FOR KRAFT PULP PRODUCTION CONSIDERING TECHNICAL AND ECONOMIC ASPECTS

SAEED MAHDAVI, HOSSEIN KERMANIAN,[*] OMID RAMEZANI[*] and SAFDAR MOLAVI*

Wood and Forest Product Research Division, Research Institute of Forests and Rangelands, 31739-44351 Karaj, Iran
[*]*Department of Pulp and Paper, Energy and New Technology Faculty, Zirab Branch, Beheshti University, Iran*

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Five successful non-indigenous clones, selected based on local adaptability from a total of fifteen, were studied for their kraft pulp production and a new ranking method based on technical and economic parameters was used to facilitate decision making in future plantation policies. Three logs were cut at the breast height of each clone with the age of 12 years. The best screen yield mean of five clones (52.58%) was achieved applying the cooking treatment combination of 170 °C, 45 min, 18% A.A., and 23% sulfidity. Physical and mechanical properties of the handsheets prepared from the pulp, namely average sheet apparent density, tear and burst indices and breaking length, were measured as 0.75 g cm^{-3}, 10.67 mN m^2 g^{-1}, 5.20 kPa m^2 g^{-1}, and 7.60 km, respectively. A pair-wise comparison with nine objectives was carried out using Expert Choice software by two unweighted and weighted (technical and economic weighting) methods. The two ranking methods indicated that Costanzo and Triplo (clones of *P. euroamericana*) are the superior and, respectively, the inferior of the clones under study, considering the objectives of the hierarchy. The other clones were ordered differently, according to the priority of each of the methods. Despite the highest annual growth rate, sheet density and tear index, Vernirobensis (clone of *P. euroamericana*) was situated second in the ranking. The results indicated that the pulp strengths of all selected clones were higher than the strength requirement for kraft liner, according to ISIRI 3054 standard.

Keywords: growth rate, kraft pulp, screen yield, paper properties, poplar clone, ranking method, Expert Choice

INTRODUCTION

In 2009, almost 360 million tons of different pulps were used as fibre furnish in papermaking industries, of which the share of wood pulp was estimated to be 160 million tons.[1] However, during the late 20th century, a global shortage of wood emerged, and consequently the paper industry was forced to look for alternative sources of fibrous raw material.[2] Serious shortage of wood in Asia and the Middle East led to planting fast-growing trees, especially poplar hybrid clones.

Selection programs have been focused on growth rate, site adaptability and resistance of poplar trees. Some literature sources have stated transgenic trees with improved growth rate, trunk shape and adaptability might have inferior fiber properties in papermaking applications compared to non-transgenic species.[3]

A great deal of research studies has been devoted to the adaptability and wood production rate of different poplar clones in Iran. At present, 50,000 ha in the northern Iran are under plantation of successful poplar species. On average, the annual 2.5 million m^3 wood production is mainly used in the building and paper industries.[4] The design of two papermaking factories located in the northern part of the country have made the application of 100% poplar wood feasible, but the wood supply can not meet the requirements of these companies.

Although annual growth rate (AGR) can be an appropriate indicator for deciding on poplar wood plantation strategies, it is not sufficient when considering suitability for papermaking applications. Therefore, many industrially important characteristics should be considered. Many studies have evaluated poplar clones in terms of their application in pulp and paper industries.[5,6,7] Many parameters with different environmental and economic importance are measured to determine the papermaking potential of each clone, though, multiple criteria need to be evaluated before ranking. Ranking can be performed both non-weighted[8] and weighted.[9]

Ranking represents an ordering of a list of items according to their importance for the particular issue under consideration. Ranking or scoring exercise is done on the basis of one identified criterion. Typically, a number of criteria are first identified to form the basis on which to compare and evaluate a set of items. Once suitable criteria have been chosen, items for evaluation are scored with respect to each criterion in turn.[10]

Making a series of judgments based on pair-wise comparisons among different parameters has been widely used in wood and paper industries.[11,12,13]

The objective of this study is to evaluate five successful poplar clones as to their potential for pulp and paper manufacturing in Iran. In addition, a supplementary clone ranking investigation based on technical and economical parameters was carried out to suggest the most suitable clones for future planning.

EXPERIMENTAL

Considering the relative success of *P. euroamericana* species in semi-arid climate, such as that of the Alborz province of Iran, four clones of this species and a clone of *P. nigra* (42/51) were selected in this study. Fifteen 1-meter long logs were cut at breast height from the following *P. euroamericana* clones: Vernirobensis (V), Costanzo (C), Triplo (T) and I-214 (I), along with *P. nigra var.* 42.51 (N) were obtained. The trees were 12 years old and their logs were debarked and the chips were prepared by a laboratory Pallmann chipper (Model X 430-120 PHT). The specifications of these clones have been summarized in Table 1.[14]

Table 1
Average growth rate and specifications of the five clones

Clone	AGR (m^{-3} ha y^{-1})	Breast height (cm)	Tree height (m)
N	20.87	21.53	18.46
V	27.45	24.60	18.59
C	22.28	22.83	17.48
T	21.91	22.03	18.44
I	22.58	22.53	18.22

After several cooking trials, the kraft pulp was produced under two sets of pulping conditions, with three constants, such as liquor to wood ratio (5:1), five cooking times (15, 30, 45, 60 and 75 minutes) and cooking temperature (170 °C) and two variables, as follows:

1. Trial A: 25% sulfidity and 20% active alkali (as Na_2O);
2. Trial B: 23% sulfidity and 18% active alkali (as Na_2O).

For each combination of variables, three replica pulps were prepared. After cooking, the hot-softened chips were disintegrated using two passes through a single disk refiner with 2 mm clearance. The produced pulp was washed on two screens of 18 and 200 mesh and the screen yield was determined after the separation of rejects. Kappa number was measured by the micro-kappa modified method (UM-246), according to TAPPI Methods.[15] The freeness was measured according to TAPPI standard T 227 om-99 and the beating of pulps was performed by a PFI mill at 0.5 mm gap and 3.33±0.1 N mm^{-1}, according to TAPPI standard[16] T 248 sp-00 to reach to 400 CSF. A specific parameter called “Beating Index” was designated to better characterize the beatability of different wood clones. It is defined as 1 ml CSF reduction of pulp per beater revolution and measured as the ratio of beater revolution to the freeness loss of pulp, therefore, pulps with a higher beating index will require more beating energy to reach the target freeness.

Fiber classification for each pulp was carried out with a Bauer-McNett Classifier with 5 screens

(14, 30, 50, 100 and 200 mesh), according to TAPPI T 233 cm-06.[16] Weighted average fiber length (WAFL) was determined as described in TAPPI T 232, by taking a small specimen from the pad of each compartment before drying.

The handsheets were prepared according to SCAN standard of M 5:67, by KCL sheet former with a basis weight of 60 g $m^{-2}$and tested for strength properties (tear index, burst index and breaking length) according to TAPPI T 220 sp-01.[16]

One-way analysis of variance (ANOVA, $^{*}P < 0.05$) was used to analyze the results. The variance and Duncan Multiple Range tests (DMRT) were conducted to show the difference between the clones. Statistical procedures were carried out using SPSS software. Expert Choice software was utilized to rank five clones according to two criteria (economic and technical aspects) and their nine parameters, such as screen yield (S.Y.), breaking length (B.L.), burst index, tear index, WAFL, average growth rate (AGR), fines content (F.C.), beating index (B.I.) and kappa number. Screen yield, AGR and fines content were considered as the economic objective and the other six parameters, including WAFL, kappa number, breaking length, burst index, tear index and beating index, were selected as technical aspects. Two methods, both weighted and unweighted, have been chosen to rank the clones according to the 9 parameters. The pair-wise comparison and prioritization process were carried out for the two criteria and the above-mentioned parameters by Expert Choice software. In order to perform a weighted ranking for the five clones of poplar, a questionnaire was filled out by three experts on the priority of the 9 important parameters. These parameters were categorized by the normalization method using Expert Choice software. To emphasize the considerable effect of the price increase of wood as a raw material for pulp and paper industry in the last several years in Iran, double value was allocated to the economic aspect. Furthermore, screen yield weight percent was determined to be 0.422, whereas a much lower value of 0.023 was selected for weight percent of kappa number, according to three experts' opinions. The weights allocated to different criteria are listed in Table 2.

The software creates a model with only one node (the goal) and displays it in the Model View's Tree View. Here, the Tree View displays the hierarchical analysis of criteria and parameters for weighted ranking (Figure 1); each item in the hierarchy is called a node. In this study, the aim was clone ranking.

The five clones were alternatives and the first way (relative comparison) was selected for prioritization.

1. Adding the objectives (clone ranking) and sub-objectives (economic and technical aspects) to Model View's Tree.
2. Finally, the mathematical best fit for the current set of judgments will be displayed in the matrix by the software and different types of graph (performance, dynamic, gradient and head to head) could be drawn.

RESULTS

The mean of screen yield and kappa number of kraft pulps of the poplars cooked under the A and B cooking conditions are given in Tables 3 and 4, respectively. Trial B is superior considering both the screen yield results and the lower chemical consumption for each clone.

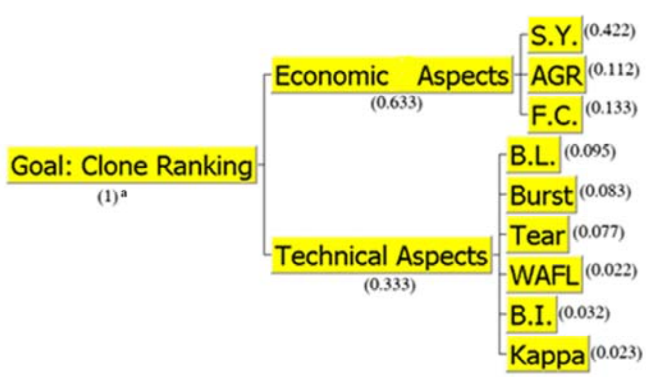

Figure 1: Hierarchical analysis of five poplar clones using Model View's tree
([a]Numbers within parenthesis show the priorities)

Table 2
Priorities of two criteria and nine parameters used for clone ranking by two methods

Criteria and parameters	Unweighted ranking priorities	Weighted ranking priorities [a]	Normalized weighted ranking priorities [b]
Economical aspects	1	0.633	1
Screen yield	1	0.422	0.633
Fines content	1	0.112	0.199
AGR	1	0.133	0.167
Technical aspects	1	0.333	0.5
Breaking length	1	0.095	0.142
Burst index	1	0.083	0.125
Tear index	1	0.077	0.116
WAFL	1	0.022	0.033
Beating index	1	0.032	0.049
Kappa no.	1	0.023	0.034

[a]Global priorities; [b]Local priorities

Table 3
Screen yield of unbleached kraft pulps of 5 poplars for 5 cooking times using trials A and B

Clone \ Cooking time (min)	Trial	15	30	45	60	75	SD
N	A	44.68	49.68	52.51	50.3	51.8	3.08
V	A	45.79	49.8	51.3	47.32	46.42	2.34
C	A	49.26	49.5	53.13	52.73	49.18	1.99
T	A	52.82	54.22	53.56	48.87	45.52	3.70
I	A	53.37	55.3	52.41	52.46	45.6	3.07
Total mean	A	49.18	51.70	52.58	50.34	47.70	1.95
N	B	50	52.20	52.02	50.52	47.90	1.75
V	B	47.10	50.48	53.65	52.24	47.98	2.77
C	B	49.37	50.39	52.7	50.50	47.08	2.04
T	B	50.33	50.45	53	52.50	49.95	1.40
I	B	51.33	56.73	53.99	50.16	49.12	3.09
Total Mean	B	49.63	52.05	53.07	51.18	48.41	1.87

Table 4
Kappa number of unbleached kraft pulps of 5 poplars for 5 cooking times using trials A and B

Clone \ Cooking time (min)	Trial	15	30	45	60	75	SD
N	A	19.69	17.51	15.63	13.27	12.83	2.89
V	A	19.19	16.86	16.10	14.26	13.72	2.19
C	A	19.20	16.57	16.10	14.66	12.78	2.38
T	A	19.69	19.20	17.39	15.82	15.02	2.04
I	A	19.47	18.70	17.55	16.50	12.71	2.64
Mean	A	19.45	17.77	16.55	14.90	13.41	2.36
N	B	27.77	24.73	16.02	15.96	14.80	5.95
V	B	25.17	21.34	17.12	16.02	15.56	4.12
C	B	36.15	21.65	18.55	15.97	14.78	6.65
T	B	42.34	21.95	18.55	17.63	14.60	5.12
I	B	21.07	18.20	17.58	17.21	16.50	1.76
Mean	B	30.50	21.57	17.56	16.56	15.25	6.18

Table 5
Freeness and beating index of unbleached kraft pulp of 5 poplar clones

Clone	Initial freeness (CSF)	Revolution	Final freeness (CSF)	Beating energy[a]
N	670	15000	397	54.94 *(b)*[b]
V	664	14000	385	50.18 *(c)*
C	670	14500	410	55.77 *(b)*
T	687	14000	386	46.51 *(d)*
I	637	14200	410	62.55 *(a)*

[a]The required revolutions for 1 mL reduction in CSF
[b] Italic letters within parenthesis show the mean statistical grouping at α = 0.05

Table 6
Fiber classification of unbleached karft pulp of 5 poplar clones

Mesh / Clone	14 (%)	30 (%)	50 (%)	100 (%)	200 (%)	Fines (%)	WAFL
N	0.75	19.57	28.39	23.43	12.71	15.15	0.84 *(b)* [a]
V	0.00	0.03	41.04	24.21	7.07	27.65	0.75 *(cd)*
C	0.88	27.09	32.09	24.92	1.03	13.99	0.91 *(a)*
T	0.75	3.33	21.92	25.65	23.53	24.82	0.71 *(d)*
I	1.20	4.14	48.70	12.17	10.02	23.77	0.80 *(bc)*

[a] Italic letters within parenthesis show the mean statistical grouping at P < 0.05

Table 7
Physical properties of unbleached kraft pulp of 5 poplar clones

Properties / Clone	Apparent density (g cm^{-3})	Tear index (mN m^2 g^{-1})	Burst index (kPa m^2 g^{-1})	Breaking length (km)
N	0.70 *(c)* [a]	9.73 *(c)*	4.37 *(c)*	6.6 *(c)*
V	0.82 *(a)*	11.68 *(a)*	5.07 *(b)*	7.7 *(b)*
C	0.73 *(bc)*	10.66 *(b)*	5.58 *(a)*	7.9 *(ab)*
T	0.76 *(b)*	10.70 *(b)*	5.33 *(ab)*	7.7 *(b)*
I	0.73 *(bc)*	10.59 *(b)*	5.64 *(a)*	8.1 *(a)*

[a] Italic letters within parenthesis show the mean statistical grouping at P < 0.05

Optimum cooking time is 45 min in both of the trials based on the highest observed screen yield. The best screen yield and kappa number were observed for clone I using trial B.

There are negligible differences in the initial freeness of the clones (Table 5). The beating index of the 5 poplar clones showed a significant difference (Duncan's test, $^*P < 0.05$). Based on the beating index calculations, I and T clones required higher and lower beating energy, respectively.

The results of fiber length classification for the kraft pulp of the 5 selected clones (Table 6) indicate a relatively high difference in the WAFL of the clones, clone C having the highest value. Clone T has the lowest WAFL, being classified as inferior based on this parameter. In addition, the results show a relatively high amount of fines in the 5 selected clones ranging from 13.99% to 27.65%. Clone C and clone V had the lowest and, respectively, the highest fines content.

Table 7 lists sheet apparent density and strength properties of the sheets prepared from the pulps of the 5 selected clones. The table shows that clones V and N had the highest and lowest sheet apparent density, respectively, and were situated in independent groups.

The results for the tear index indicated that clone V with the maximum tear index (group A) was superior to the others. The best pulp burst index and breaking length was presented by clone I, but Duncan's test grouped I and C clones similarly ($^*P < 0.05$).

Figure 2 shows the unweighted ranking of the 5 selected clones. Both ranking methods of the 5 selected clones of poplars rank clone C as the best choice, considering the objective of the experiment (Figures 2, 3, 4 and 5). Clone T is ranked as an inferior clone both by unweighted and weighted ranking (Figures 2 and 3); though considering the economic or technical aspects, the ranking of this clone would be different (Figures 4 and 5). It is notable that clone I was situated one step higher in weighted ranking, compared to unweighted ranking (Figures 2 and 3).

It is possible to rank the 5 clones individually with respect to each criterion (Figures 4 and 5). The individual ranking might give different results. For instance, clone N was ranked second based on economic aspects, but last, at a significant distance from the other clones, when technical aspects were considered. Therefore, for clone selection, pulp producers can decide based on either economic importance or final product technical specifications.

DISCUSSION

Fast-growing clones reach a harvestable size more rapidly and therefore contain greater proportions of juvenile wood (juvenile wood is the first few years' growth near the pith), compared to current aspen harvests.[17] A higher proportion of juvenile wood in the fast-growing trees, due to AGR increase, will affect pulping and pulp properties.[18,19]

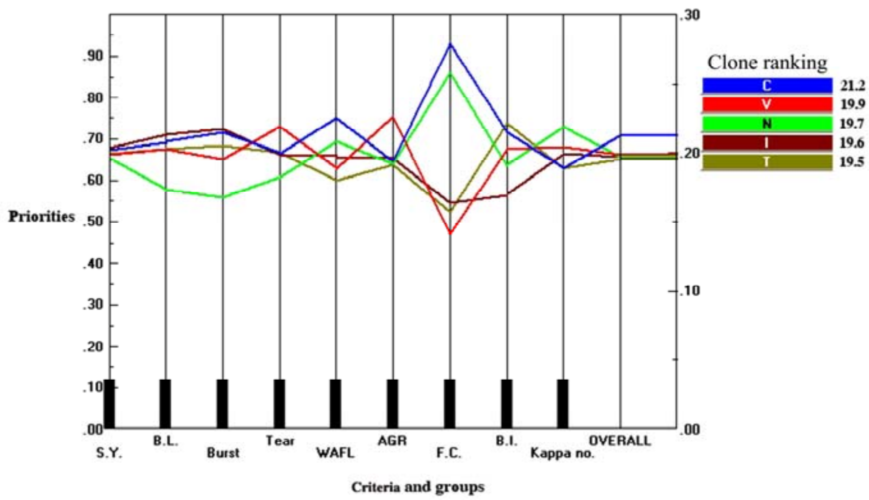

Figure 2: Unweighted ranking of five poplar clones using nine parameters without prioritizing

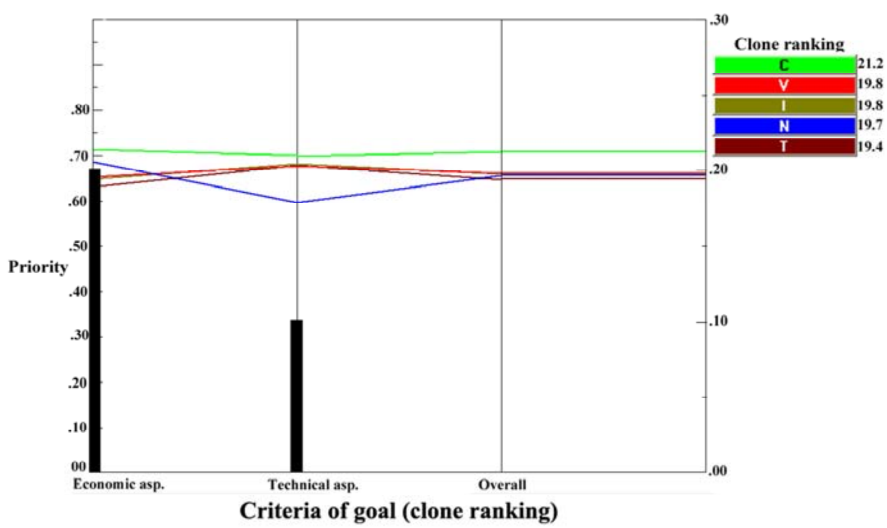

Figure 3: Weighted ranking of five poplar clones using two criteria

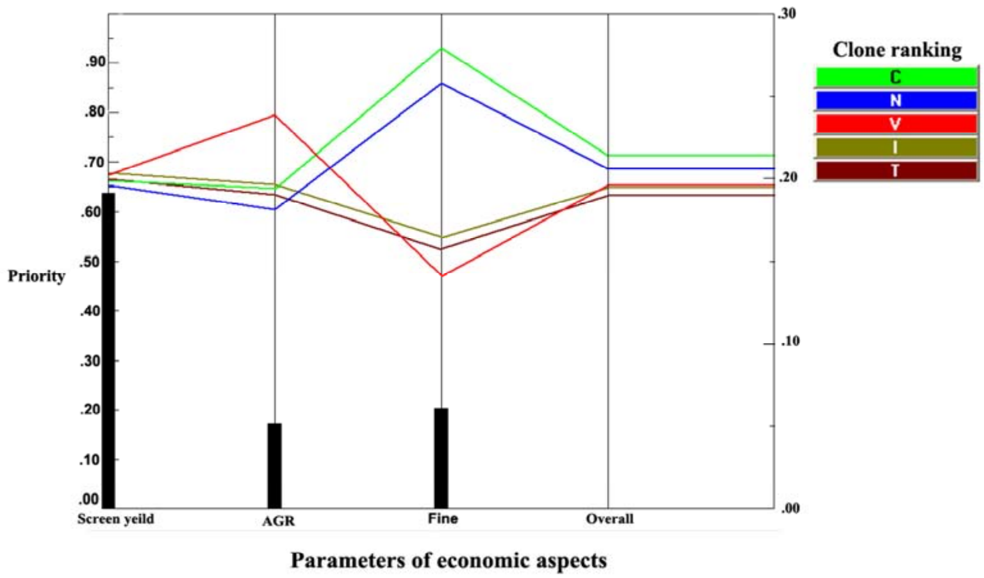

Figure 4: Weighted ranking of five poplar clones using three parameters of economical aspects

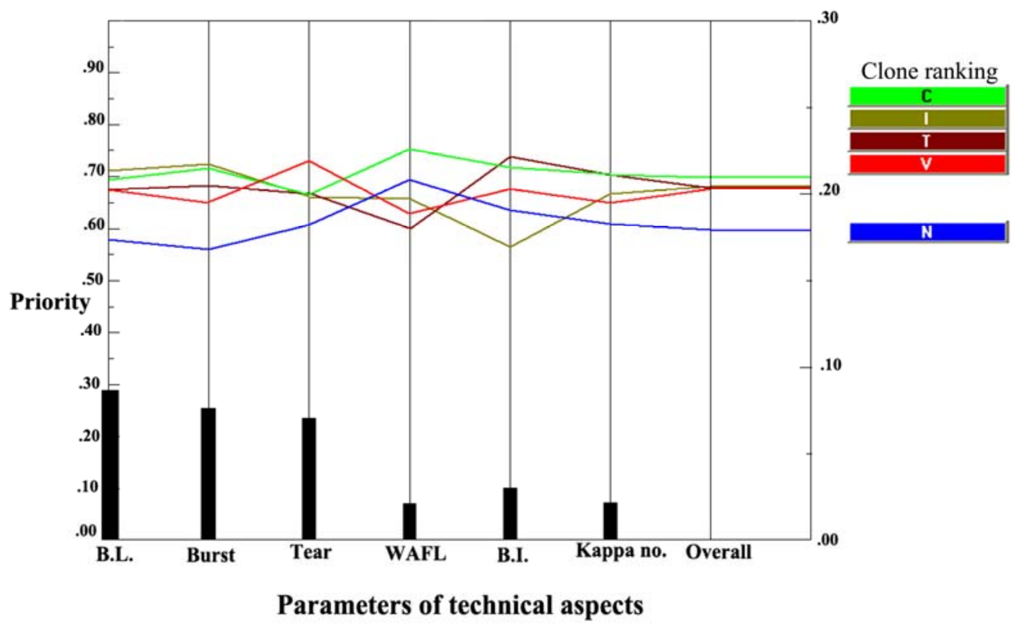

Figure 5: Weighted ranking of five poplar clones using six parameters of technical aspects

According to the aforementioned results, it was considered that biometry factors, like AGR, could not solely characterize the superior clone ranking and give a definite decision for plantation plans. For instance, despite the higher AGR in clone V and the consequent profitability due to rapid capital return, this clone was ranked third compared with other clones because of high fines content and low screen yield (economic parameters, Figure 4). It's suggested that, in general, hybrid poplars have a high proportion of very short cells (<0.2 mm) compared with trembling aspen.[18]

The variation in pulp yield correlated well with the alpha-cellulose content of the wood, however, higher yields do not always lead to higher pulp production due to differences in specific gravity (digester packing).[19]

Cell wall thickness and coarseness are valuable indicators of fiber quality. They are inadequate for completely characterizing fiber quality, since fibers having similar wall thickness can have very different coarseness or vice versa.[18] Lumen diameter and flexibility coefficient also could affect the beating of pulp. The larger the lumen diameter, the better will be the beating of pulp, because of the penetration of liquids into the empty spaces of the fibers.[20] The high fiber flexibility, especially in poplar, can cause slipping under the beater bars, so refining energy consumption is usually higher, compared to that for other hardwoods.

The derived values of screen yield and rejects of kraft pulps showed that trial B is more efficient than trial A, with respect to economic and environmental aspects. Rejects represent the fraction of pulp retained on a screen, which can be a good indicator of the uniformity of the raw material or the inefficiency of chemical treatment.[21] Kraft pulping screen yield and kappa number were found to be of 56% and 20%, respectively,[22] while the reported values for these parameters were lower for the first (yield) and higher for the latter (kappa) in the present study (Tables 3 and 4). The screen yield and kappa number differences were attributed to the intrinsic differences among the poplar clones observed in the current and the above-cited study, particularly regarding age, wood density, fiber characteristics, chemical composition, as well as applied cooking conditions.

With the exception of tear index, the strength values of the unbleached kraft pulps of the five poplar clones were lower by about 10 to 15%, in comparison with the results reported in literature.[22,23] In contrast, the value of tear index was 20% higher, which makes the wood pulps suitable for products such as tissue and board. The tear strength of paper depends on the length of fibers, intrinsic fiber strength, cell wall thickness, fiber coarseness and the inter fiber bonding. Products, such as printing and writing papers, should be made of juvenile fiber, in contrast with other paper products requiring high tear strength.[24]

Kellomäki[18] stated that higher sheet density and lower bulk are the important pulp and paper characteristics of juvenile wood. The high values of sheet apparent density and tear index in clone V are predominantly affected by AGR (Table 1).

The increase in fiber bonding improves tensile strength, which is further improved by the flexibility and bonding tendency of individual fibers. When paper with high tensile or burst strength is required, thin-walled cells and a low wood density are advantageous. High amounts of coarse fibers also lengthen the beating time and make sheet formation more difficult.[24] These characteristics would affect the position of the clones in weighted ranking according to technical parameters (Figure 5).

In general, both ranking methods indicated clone C and clone T as the superior and, respectively, the inferior out of the clones under study, based on the double weight of economic and technical aspects. It is evident that the ranking could be different, as a function of the product requirements and geographical location. For example, a higher priority value could be given to screen yield and fines content as economic parameters, in the Middle East, particularly in Iran, because of wood shortage and raw material supply costs (Table 7). A yield difference of 0.7% may seem rather small, but a pulp production rate of 1000 t d^{-1} requires 12000 t more wood (on an oven-dry basis) annually,[25] which can easily translate into a cost increase of a million dollars or more a year!

CONCLUSION

In the future, the raw material for the pulp industries will be increasingly supplied from fast-growing short-rotation plantations. The proportion of juvenile wood in the raw material flow will therefore increase. The ranking of the 5 selected clones of poplar indicated that clones C and T are the superior and the inferior, respectively, considering the objective of the hierarchy analysis. There were differences in the ordering of the other clones under study, when applying different ranking methods. In spite of the highest AGR in clone V, which is assumed to be a major factor in short-rotation woody crops, it was situated second in ranking. The breaking length, burst index and tear index of these pulps were found to range from 6.6 to 8.1 km, 4.37 to 5.64 kPa m^2 g^{-1}, and 9.73 to 11.68 mN m^2 g^{-1}, respectively. In order to gain good strength properties, long fiber addition is required to reinforce the produced kraft pulp, especially in clone C. Furthermore, the results indicate that the five selected clones are suitable for producing different paper grades, which require high tear strength, e.g. tissue, kraft liner, and printing paper. The pulp strength of the five clones was higher than that of kraft liner, which has been characterized by ISIRI 3054 standard.[26]

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