The function for estimating the separation efficiency of the wheat flour milling process

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Abstract Considering the significant differences between the chemical composition of the kernel layers, distribution of chemical compounds in intermediate, final and subproducts of the milling process come as a result of the level of dissociation achieved during the milling process. These differences serve as a basis for the mill process control. Ash determination is probably the most widely used tool while even greater differences exist in cellulose and especially starch content. In this work efficiency function has been defined and used to evaluate the relative efficiency of the separation of endosperm from the outer pericarp layers of the kernel. It is based on quantity rates (flour extraction and subproducts yield) and qualitative analyses (starch and cellulose content in the wheat, flour and subproducts).

Keywords Wheat · Flour milling · Efficiency function · Separation

Introduction

The aim of the wheat flour milling process, along with the size reduction, is to obtain the best possible dissociation of the starchy endosperm from the other parts of the grain to yield the white flour (Antoine et al. 2004). The flour is produced from wheat through comprehensive stages of grinding and separation (Shekara et al. 2011). The separation should ideally occur at the level of the endosperm-

aleurone layer interface. Although the aleurone layer is part of endosperm, it is separated as part of the bran during the milling process (Peyron et al. 2002). However, it is impossible to mill flour completely free of bran contamination. Milling tends to concentrate various section of the kernel into different flour mill streams but the complete separation of the anatomic parts can not be achieved. The objective in efficient milling is to approach this goal as closely as possible (Posner and Hibbs 2005).

Ash determination is of great value to the miller because it is a relatively accurate index of the separation of endosperm from pericarp and germ in any particular flour. Ash is concentrated in the bran with over half the total in the pericarp, testa and aleurone (Kent 1975). The most widely used single measurement of milling efficiency from a technical viewpoint is accumulated ash curve. This can be constructed from the flow rate, percentage of ash and moisture level of all the mill's intermediate flour streams (Posner 1991; Sakhare and Inamdar 2011). Along with the ash content, Kim and Flores (1999) used color and bran speck counts to determine the bran contamination in wheat flours.

The mill's intermediate streams also differ in protein quantity and quality (Nelson and McDonald 1977), the quantity and properties of the pentosans (Ciaccio and D'Appolonia 1982), contents of free lipids and their fatty acid composition (Prabhasankar and Haridas Rao 1999; Prabhasankar et al. 2000a, b), distribution of enzymes (Rani et al. 2001), fibre composition (Escarnot et al. 2010). Jensen et al. (1982) suggested the method for quantifying pericarp, aleurone, and endosperm in wheat milling fractions by their auto-fluorescence characteristics. Antoine et al. (2004) used starch, phytates, *p*-coumaric acid and dehydrotrimer of ferulic acid as markers to quantify the proportion of starchy endosperm, aleurone cell content, aleurone walls, intermediate layer and outer pericarp in bran products.

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However, in the industrial conditions, dealing with day to day problems associated with commercial production, some of this analysis is still impracticable and expensive. Compared to ash content even greater differences between the anatomic parts of the wheat kernel exist in cellulose and especially starch content. The idea was to define the efficiency function that is applicable in industry.

Efficiency function

Assuming that material represents the mixture of two components (component 1 and 2), the aim of separation process is to obtain the best possible dissociation between them. Separation results in two fractions, fraction 1 - mainly consist of component 1 and fraction 2 - mainly consist of component 2. In ideal situation (complete separation) fraction 1 contains only component 1 (without component 2) while fraction 2 contains only component 2 (without component 1). In reality, the complete separation rarely occurs and certain amount of components 2 and 1 are present in fractions 1 and 2 respectively.

The following symbols represent:

Q	mass flow of the native feed
$a_{1/2}$	weight fraction of the components 1 and 2 in native feed
$P_{1/2}$	mass flow of the fractions 1 and 2
$B_{1/2}$	yield of fractions 1 and 2 relative to the native feed
φ_{11}	weight fraction of the component 1 in fraction 1
φ_{21}	weight fraction of the component 2 in fraction 1
φ_{12}	weight fraction of the component 1 in fraction 2
φ_{22}	weight fraction of the component 2 in fraction 2

having : $a_1 + a_2 = 1$; $B_{1/2} = P_{1/2}/Q$; $B_1 + B_2 = 1$;
 $\varphi_{11} + \varphi_{21} = 1$; $\varphi_{12} + \varphi_{22} = 1$

(1)

Considering the fraction 1, the efficiency of separation increases with the increase of φ_{11} and decrease of φ_{21} with ideal situation having:

$$\varphi_{11} = 1 \text{ and } \varphi_{21} = 0 \quad (2)$$

Considering the fraction 2, the efficiency of separation increases with the increase of φ_{22} and decrease of φ_{12} with ideal situation having:

$$\varphi_{22} = 1 \text{ and } \varphi_{12} = 0 \quad (3)$$

The separation efficiency can be defined as a ratio of “achieved level of purity” relative to the “maximum level of purity” (ideal situation). For the fraction 1, achieved level of purity represent difference between φ_{11} and a_1 ,

while for the fraction 2 can be defined as difference between φ_{22} and a_2 :

$$\varphi_{11} - a_1; \varphi_{22} - a_2 \quad (4)$$

Maximum level of purity corresponds to ideal situation having:

$$1 - a_1; 1 - a_2 \quad (5)$$

Eqs. (6) and (7) define the separation efficiency considering fractions 1 and 2 respectively:

$$E_1 = \frac{\varphi_{11} - a_1}{1 - a_1} \quad (6)$$

$$E_2 = \frac{\varphi_{22} - a_2}{1 - a_2} \quad (7)$$

The over all separation efficiency also depends on the yield of fractions 1 and 2 (B_1 and B_2) because high level of purity can be achieved but with cost of low fraction yield. Following the increase of the fraction yield, the relative contribution of achieved separation efficiency considering the observed fraction (E_1 or E_2) to overall separation efficiency (E) also increases:

$$E = B_1 E_1 + B_2 E_2; E = B_1 \frac{\varphi_{11} - a_1}{1 - a_1} + B_2 \frac{\varphi_{22} - a_2}{1 - a_2} \quad (8)$$

Separation efficiency reaches its maximum with $E=1$ (following $E_1=1$ and $E_2=1$) which corresponds to the ideal situation.

To study the effectiveness of the wheat flour milling process one needs quantity rates (break release, flour yield, particle size distribution of the output) and qualitative analyses (ash, protein, starch content in the flour or size fractions of the output etc.) (Farrell and Ward 1965). The relative amounts of products are expressed as functions of quantity and quality. Practically, the efficiency of the milling process is influenced both by the yields of the final (B_1) and by-products (B_2) as well as their “purity” or the absence of endosperm in by-products and bran in final products. Most of the approaches use some of the constituents as an indicator of presence of certain grain tissue in flour mill stream. Contrarily this model is based on an absence of certain constituent as an indicator of absence of tissue in the mill stream. Determination of the starch content in the by-products (bran) of the flour milling process serves as a measurement of the loss of endosperm in bran. Determination of flour cellulose content serves as a measurement of bran contamination of the flour. This is reason why it is necessary first to know starch content (a_1) and cellulose content (a_1^*) in the wheat (native feed). Knowing a_1 and a_1^* , the values of a_2 and a_2^* defined as a content of all other components in the wheat except starch and cellulose respectively, are coming from Eq. (1).

The absence of cellulose in flour indicates the high separation efficiency. Presuming ideal dissociation of endosperm

Table 1 Flow rate and yield of the final and by-products in the investigated commercial mills

Material	Mill A (180 t/day)			Mill B (120 t/day)			Mill C (90 t/day)			Mill D (30 t/day)		
	Flow rate [kg/min]	Yield (%)	CI	Flow rate [kg/min]	Yield (%)	CI	Flow rate [kg/min]	Yield (%)	CI	Flow rate [kg/min]	Yield (%)	CI
Wheat on 1st break	123.4±0.45	100	123.4±1.12	83.0±0.26	100	83.0±0.66	62.6±0.23	100	62.6±0.57	21.6±0.17	100	21.6±0.43
Flour T-400 (ash(%) _{dm} ≤0.45)	4.0±0.06	3.2	4.0±0.14	–	–	–	–	–	–	–	–	–
Flour T-500 (0.45<ash(%) _{dm} ≤0.55)	80.7±0.21	65.4	80.7±0.52	65.2±0.21	78.5	65.2±0.52	46.4±0.15	74.1	46.4±0.38	15.9±0.10	73.6	15.9±0.25
Flour T-850 (0.80<ash(%) _{dm} ≤0.90)	9.6±0.15	7.8	9.6±0.38	–	–	–	–	–	–	0.8±0.06	3.7	0.8±0.14
Waffle Flour	4.0±0.10	3.2	4.0±0.25	–	–	–	–	–	–	–	–	–
Semolina	0.7±0.06	0.6	0.7±0.14	–	–	–	–	–	–	–	–	–
Mill feed	24.4±0.11	19.8	24.4±0.29	17.8±0.06	21.5	17.8±0.14	16.2±0.10	25.9	16.2±0.25	4.9±0.06	22.7	4.9±0.14

Values are mean±standard deviation of three independent determinations

CI represents 95 % confidence interval given by Student's t-distribution

Table 2 Starch, cellulose and ash content in the final and by-products in the investigated commercial mills

Material	Mill A			Mill B			Mill C			Mill D		
	Starch content (% _{dm})	CI	Cellulose content (% _{dm})	Starch content (% _{dm})	CI	Ash content (% _{dm})	Starch content (% _{dm})	CI	Cellulose content (% _{dm})	Starch content (% _{dm})	CI	Ash content (% _{dm})
Wheat on 1st break	69.6±0.44	69.6±1.08	2.30±0.021	2.30±0.052	1.65±0.025	1.65±0.063	70.6±0.40	70.6±1.00	2.16±0.032	2.16±0.080	1.55±0.023	1.55±0.057
Flour T-400 (ash(%) _{dm} ≤0.45)	82.3±0.40	82.3±0.99	0.14±0.006	0.14±0.014	0.43±0.010	0.43±0.025	–	–	–	–	–	–
Flour T-500 (0.45<ash(%) _{dm} ≤0.55)	81.0±0.17	81.0±0.43	0.16±0.006	0.16±0.014	0.58±0.015	0.58±0.038	83.1±0.32	83.1±0.80	0.21±0.011	0.21±0.029	0.60±0.017	0.60±0.043
Flour T-850 (0.80<ash(%) _{dm} ≤0.90)	76.7±0.31	76.7±0.76	0.27±0.015	0.27±0.038	0.85±0.026	0.85±0.066	–	–	–	–	–	–
Waffle Flour	80.7±0.61	80.7±1.51	0.15±0.006	0.15±0.014	0.56±0.017	0.56±0.043	–	–	–	–	–	–
Semolina	85.1±0.40	85.1±1.00	0.11±0.006	0.11±0.014	0.39±0.006	0.39±0.014	–	–	–	–	–	–
Mill feed	17.5±0.26	17.5±0.66	11.03±0.035	11.03±0.087	6.20±0.035	6.20±0.086	22.1±0.26	22.1±0.66	8.98±0.032	8.98±0.080	5.02±0.035	5.02±0.087
Wheat on 1st break	66.9±0.36	66.9±0.89	2.70±0.025	2.70±0.062	1.68±0.023	1.68±0.057	70.1±0.32	70.1±0.80	1.64±0.026	1.64±0.066	1.60±0.026	1.60±0.066
Flour T-500 (0.45<ash(%) _{dm} ≤0.55)	81.7±0.31	81.7±0.76	0.19±0.017	0.19±0.043	0.60±0.017	0.60±0.043	84.0±0.32	84.0±0.80	0.20±0.023	0.20±0.057	0.59±0.015	0.59±0.038
Flour T-850 (0.80<ash(%) _{dm} ≤0.90)	–	–	–	–	–	–	81.6±0.32	81.6±0.80	0.37±0.015	0.37±0.038	0.74±0.026	0.74±0.066
Mill feed	30.2±0.15	30.2±0.38	9.87±0.043	9.87±0.108	4.75±0.026	4.75±0.066	31.1±0.26	31.1±0.66	6.73±0.043	6.73±0.108	5.03±0.031	5.03±0.076

Values are mean±standard deviation of three independent determinations

CI represents 95 % confidence interval given by Student's t-distribution

dm dry matter basis

Table 3 Separation efficiency in the investigated industrial mills calculated using the proposed function

	Mill A	Mill B	Mill C	Mill D
B ₁	0.802	0.785	0.741	0.773
B ₂	0.198	0.215	0.259	0.227
φ_{21}^*	0.9983	0.9979	0.9981	0.9979
a_2^*	0.9770	0.9784	0.9730	0.9836
φ_{22}	0.8250	0.7790	0.6980	0.6890
a_2	0.3040	0.2940	0.3310	0.2990
E	0.891	0.856	0.831	0.800

and bran, cellulose content in flour is $\varphi_{11}^* = 0$ (in reality it can never be 0, because small amount of cellulose is normally present even in the central part of the endosperm), while the content of all other components in flour (except cellulose) is $\varphi_{21}^* = 1$. Considering flour (fraction 1) separation efficiency can be defined as:

$$E_1 = \frac{\varphi_{21}^* - a_2^*}{1 - a_2^*} \quad (9)$$

Complete separation of the anatomic parts of the wheat kernel also means that there are no endosperm particles in by-products (bran) with starch content $\varphi_{12} = 0$ while the content of all other components (except starch) is $\varphi_{22} = 1$. Considering bran (fraction 2) separation efficiency can be defined as:

$$E_2 = \frac{\varphi_{22} - a_2}{1 - a_2} \quad (10)$$

Having B₁ and B₂ as the yields of the final (flour) and by-products (bran) of the wheat milling process the overall separation efficiency (E) can be defined as:

$$E = B_1 \frac{\varphi_{21}^* - a_2^*}{1 - a_2^*} + B_2 \frac{\varphi_{22} - a_2}{1 - a_2} \quad (11)$$

Separation efficiency reaches its maximum with E=1 (following E₁=1 and E₂=1) which corresponds to ideal situation that is complete separation between endosperm and bran.

Materials and methods

Function was tested using the samples obtained from four commercial mills of different milling capacity (Table 1). Before sampling, investigated commercial mills were checked for any kind of disturbances in the process and sampling was carried out with balanced load to machines. Because of differences in stream quantities, the streams are collected for different lengths of time (30–60 s). When inserted into the Table 1, all the streams are corrected to the same length of time (1 min). Samples were taken after the air locks of the pneumatic conveying system to avoid any potential influence of air from pneumatic system on material flow. Three set of samples were collected and for each sample, starch, cellulose and ash content have been determined according to Ewers polarimetric method (ISO 10520 1997), Kirschner-Ganakova's procedure for cellulose (Ćirić et al. 1975) and ICC standard method no.104/1 (1990), respectively. The results are expressed as mean±standard deviation and as 95 % confidence interval given by Student's t-distribution. The mean values of corresponding data are used to calculate the separation efficiency according to Eq. (11).

Results and discussion

Flour extraction (Table 1) as well as the basic chemical composition of the final and by-products (Table 2) were on the usual level for industrial flour milling process. Ash, protein and cellulose content increase while starch content decreases from the inner to the outer part of the wheat kernel (Kent 1975). As expected, the increase of the ash content is followed by the decrease of the starch content and increase of the cellulose content (Table 2). Considering the milling efficiency, it is very important that the mentioned trends are less emphasized in the final products (flour) compared to ones in by-products (millfeed).

Table 3 contains the parameters as well as separation efficiency (E) calculated upon the data presented in Tables 1 and 2.

The following example illustrates the calculation based on the proposed model for the data from industrial mill B:

Starch content in the wheat – 70.6(%) $\Rightarrow a_1 = 0.706 \Rightarrow a_2 = 0.294$

Cellulose content in the wheat – 2.16(%) $\Rightarrow a_1^* = 0.0216 \Rightarrow a_2^* = 0.9784$

Cellulose content in the flour – 0.21(%) $\Rightarrow \varphi_{11}^* = 0.0021 \Rightarrow \varphi_{21}^* = 0.9979$

Starch content in the by-products – 22.1(%) $\Rightarrow \varphi_{12} = 0.221 \Rightarrow \varphi_{22} = 0.779$

Flour yield – 78.5(%) $\Rightarrow B_1 = 0.785$

By-products yield – 21.5(%) $\Rightarrow B_2 = 0.215$

$$E = 0.785 \frac{0.9979 - 0.9784}{1 - 0.9784} + 0.215 \frac{0.779 - 0.294}{1 - 0.294} = 0.856$$

In the cases when two or more flour types are extracted in the milling process (mill A and D), separation efficiency was calculated using Eq. (12) in which subscript-n denote the corresponding flour type.

$$E = B_{11} \frac{\varphi_{211}^* - a_2^*}{1 - a_2^*} + B_{12} \frac{\varphi_{212}^* - a_2^*}{1 - a_2^*} + B_{1n} \frac{\varphi_{21n}^* - a_2^*}{1 - a_2^*} + B_2 \frac{\varphi_{22} - a_2}{1 - a_2} \quad (12)$$

It is impossible to obtain flour completely free of bran contamination as well as certain amount of endosperm goes with the milling by-products. These byproducts are collectively referred as millfeed. It is not a single homogenous stream but a collection of several streams and term millfeed is applied to any one of the fractions of the kernel left after flour removal (coarse bran, fine bran, shorts, and feed middlings) (Saunders et al. 1975). Its composition varies, depending on mill operation and wheat variety. The starch content of the various millfeeds can go from around 5 % (coarse bran) up to 40 % (feed middlings) (Fellers et al. 1966a, b) so a rough calculation suggest that starch content in the millfeed of around 18–25 % can be consider as an indicator of relatively high milling efficiency (Мерко et al. 1983). However, it depends on the adjustment of the mill and a selection of flours that are extracted in the process. It's obvious that separation efficiency has significant negative correlation with starch content in the milling by-products ($r = -0.956$).

Commercial mills differ in milling capacity, approach to wheat conditioning, technical efficiency of machines, roll gap settings, sieving conditions and etc. Separation efficiency (E) can be used to compare milling performances of different commercial mills (especially if they use the wheat of relatively same quality), but it is even better suited for comparisons of the separation efficiency achieved within the same mill. The function should react to changes in the adjustment of mill and help to optimize the recovery of milling by-products by putting you in the control of the parameters, such as cellulose and starch content, that influence the recovery of bran and middlings.

Conclusion

The proposed efficiency function is based on the data such as flour and bran yield that are practically determined on a daily bases. Also, today lot of the mills uses NIR technology for real-time, on-line control of the milling process. It can be attached to any spout in the mill for evaluation of the flowing material or flour qualitative characteristics that can

influence milling performance. Using NIR it is relatively easy to monitor data such as starch and cellulose content of wheat, flour and by-products. This function offers rapid relative measurement sensitive to changes in the mill in order to make a processing response to these changes.

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References

- Antoine C, Peyron S, Lullien-Pellerin V, Abecassis J, Rouau X (2004) Wheat bran tissue fractionation using biochemical markers. *J Cereal Sci* 39:387–393
- Ciacco CF, D'Appolonia BL (1982) Characterization and gelling capacity of water-soluble pentosans isolated from different mill streams. *Cereal Chem* 59(3):163–166
- Ćirić D, Vujičić B, Bardić Ž (1975) Handbook for quality control of raw materials and fruit and vegetable products. Faculty of Technology, Novi Sad, p 227
- Escarnot E, Agneessens R, Wathelet B, Paquot M (2010) Quantitative and qualitative study of spelt and wheat fibres in varying milling fractions. *Food Chem* 122:857–863
- Farrell EP, Ward AB (1965) Flow rates and analyses for ash and protein of all streams in the Kansas State University pilot flour mill. *Assoc Oper Millers Tech Bull*, March:2842–2847
- Fellers AD, Sinkey V, Shepherd DA, Pence WJ (1966a) Solubilization and recovery of protein from wheat millfeeds. *Cereal Chem* 43:1–13
- Fellers AD, Shepherd DA, Bellard JN, Mossman PA (1966b) Protein concentrates by dry milling of wheat millfeeds. *Cereal Chem* 43:715–725
- ICC Standard No.104/1 (1990) Determination of ash in cereals and cereal products. International Association for Cereal Science and Technology, Vienna, Austria, pp 1–4
- ISO 10520 (1997) Native starch – Determination of starch content – Ewers polarimetric method. International Organization for Standardization, Geneva, pp 1–8
- Jensen SVA, Munck L, Martens H (1982) The botanical constituents of wheat and wheat milling fractions. I. Quantification by autofluorescence. *Cereal Chem* 59(6):477–484
- Kent NL (1975) Technology of Cereals with special reference to wheat. Pergamon press, Oxford
- Kim YS, Flores RA (1999) Determination of bran contamination in wheat flours using ash content, color, and bran speck counts. *Cereal Chem* 76(6):957–961
- Мерко ИТ, Моргун ВА, Погирной НЕ (1983) Структура и эффективность технологических процессов производства муки. Колос, Москва
- Nelson PN, McDonald CE (1977) Properties of wheat flour protein in flour from selected mill streams. *Cereal Chem* 54:1182–1191
- Peyron S, Surget A, Mabilie F, Autran JC, Rouau X, Abecassis J (2002) Evaluation of tissue dissociation of durum wheat grain generated by the milling process. *J Cereal Sci* 36:199–208
- Posner ES (1991) Wheat and flour ash as a measure of millability. *Cereal Foods World* 36:626–629
- Posner ES, Hibbs AN (2005) Wheat flour milling. American Association of Cereal Chemists, Minnesota
- Prabhasankar P, Haridas Rao P (1999) Lipids in wheat flour streams. *J Cereal Sci* 30:315–322

- Prabhasankar P, Sudha ML, Haridas Rao P (2000a) Quality characteristics of wheat flour milled streams. *Food Res Int* 33:381–386
- Prabhasankar P, Vijaya Kumar M, Lokesh BR, Haridas Rao P (2000b) Distribution of free lipids and their fractions in wheat flour milled streams. *Food Chem* 71:97–103
- Rani KU, Prasada Rao UJS, Leelavathi K, Haridas Rao P (2001) Distribution of enzymes in wheat flour mill streams. *J Cereal Sci* 34:233–242
- Sakhare SD, Inamdar AA (2011) The cumulative ash curve: a best tool to evaluate complete mill performance. *J Food Sci Technol*. doi:[10.1007/s13197-011-0549-z](https://doi.org/10.1007/s13197-011-0549-z)
- Saunders RM, Connor MA, Edwards RH, Kohler GO (1975) Preparation of protein concentrates from wheat shorts and wheat millrun by a wet alkaline process. *Cereal Chem* 52:93–100
- Shekara P, Kumar VP, Hosamane GG (2011) Gravity flow operated small electricity generator retrofit kit to flour mill industry. *J Food Sci Technol*. doi:[10.1007/s13197-011-0406-0](https://doi.org/10.1007/s13197-011-0406-0)