Separation & Purification Reviews
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597294

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To cite this Article Vose, J. R.(1978) 'Separating Grain Components by Air Classification', Separation & Purification Reviews, 7: 1, 1 — 29
To link to this Article: DOI: 10.1080/03602547808066053
URL: http://dx.doi.org/10.1080/03602547808066053

SEPARATION AND PURIFICATION METHODS, 7(1), 1-29 (1978)

SEPARATING GRAIN COMPONENTS BY AIR CLASSIFICATION

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I. INTRODUCTION

The use of air as a means of effecting particle separation is one of the oldest technologies known to man. The development of various commercial air classifiers has, however, led in recent years to a renewed interest in the application of this technique to the fractionation of heterogeneous particulates into sub-groups of fairly uniform size based on particle density and mass. Early applications of air classification, and still the most commonly found, are in the chemical, dyestuffs, ceramics and white clay industries to form products sharply graded in the 2 to 60 micron range.

It has been known for many years that the milling process, in its various forms, when applied to cereal grains produces flour containing a range of particle sizes. Sieve analysis readily demonstrates that the finest particles of the flours contain higher protein levels than the coarser fractions of the flour.
Air classification applied to cereal grains produces protein displacement by permitting separation of the high protein fine particles, and this phenomenon is considered by many to be the most important recent development in milling technology. This is largely because it permits the creation of a range of products from a normal grain flour, each product differing in its chemical and

physical characteristics from the next, and accordingly suits a variety of different applications.

It is the object of this review to cover some of the developments of this concept of protein displacement as applied to a variety of cereal grains, tubers and grain legumes. The discussion will include a brief outline of the principles of air-classification, the applications and ramifications of the technique - first to wheat grain, and then to some of the more recent uses of the technology in other vegetable protein separations.

II. THE CLASSIFYING PRINCIPLE

In a classifier, particles of diameter (d), and density (ps) are exposed to two opposing forces. First, the centrifugal force (F) which may be produced by a revolving rotor and secondly, the fluid resistance or frictional force (R) whose centripetal direction is produced by the air current. These relationships are shown in the following equations:

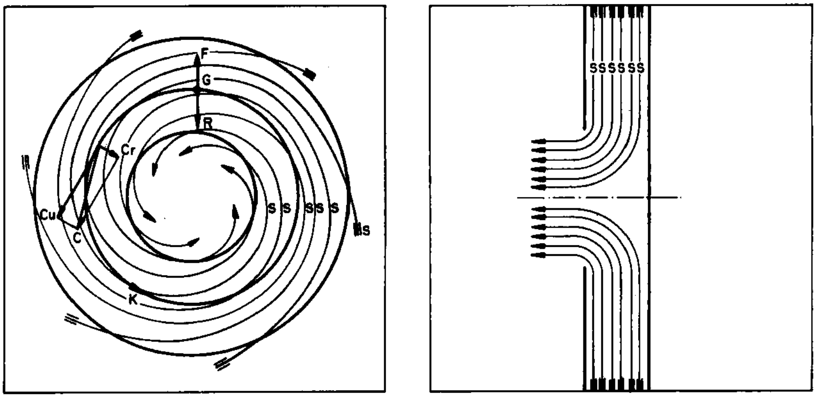
1. $F = \frac{\pi d^3}{6} (ps - pg) \frac{U_\theta^2}{r}$

2. $R = 3\pi\mu \, dUr$

3. $d_{th} = \frac{1}{U_\theta} \left(\frac{18\mu r \, Ur}{ps-pg} \right)^{\frac{1}{2}}$

where:
μ= gas viscosity (g/cm/sec)
U_θ= peripheral velocity (cm/sec)
U_r= centripetal directional velocity of gas (cm/sec)
r= rotor radius (cm)
d = particle diameter (cm)
ps = density of particle (g/cc)
pg = density of gas (g/cc)
d_{th}= theoretical limit of particle diameter (ref. 1)

It is generally assumed that the fluid resistance obeys the principles of Stokes' Law. The equations presented above are based on the classification of spherical particles; for alternative shapes the equations would require incorporation of a correction factor. These principles are shown diagrammatically in figure 1.



F = CENTRIFUGAL FORCE.
R = FRICTIONAL FORCE.
G = CUT SIZE PARTICLE.
K = CIRCULAR PATH.

S = SPIRAL FLOW LINE.
C = AIR VELOCITY.
Cu = PERIPHERAL COMPONENT.
Cr = RADIAL COMPONENT.

FIGURE 1

The forces present in the spiral flow of an air classifier (after reference 2).

Perhaps the most commonly used system is that developed by the Alpine Aktiengesellschaft of West Germany, in their range of Mikroplex Spiral air classifiers. In these units, air flows inwards in a spiral path; particles entrapped in this air flow are subjected to the two antagonistic forces F and R. Larger, higher density particles are dominated by the mass-dependent centrifugal force, and the smaller, less dense particles by the frictional force proportional to the particle diameter.

When the forces F and R are in exact equilibrium, equations (1) and (2) above may be assumed equal. This point is termed the "cut size" for a definite size of particles. In order to obtain optimized sharp separations, the equilibrium of forces should be effective at all points along the spiral flow. This is also important for the axially adjacent layers of the classifying chamber where the wall vorticity may be eliminated by rotating the walls in the direction of the air flow.

The actual cut-size achieved depends on the spiral gradient, the peripheral component (Cu) and the absolute dimension of the classifying chamber. Adjustment of the cut size can be managed by varying these first two factors; the range of the cut size is determined by the dimensions of the classifier chamber. Figure 2 illustrates a cross-section through a Mikroplex Spiral Air Classifier type MP.

The efficiency in flour separation or classification refers to the percentage of fines collected as the desired product when classifying a raw material at a given cut-point. In theory, a 100% efficiency is believed possible, but in practice efficiency may vary from 50-80%. This efficiency depends on several factors such as the amount of material at or below the required cut-point in the raw product, material cohesiveness etc. The percentage efficiency can be controlled by the particle

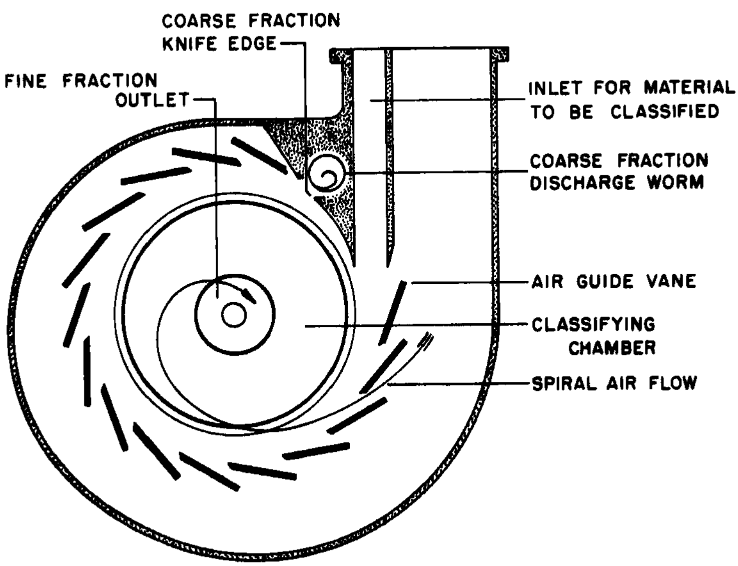


FIGURE 2

Cross-section through a Mikroplex Spiral Air Classifier type MP (after reference 2).

distribution of feed material, cut-point etc. A method for computing the separation efficiency is based on Newton's Efficiency expressed as:-

$$E = \frac{(b - a)(a - c)}{a(1 - a)(b - c)} \times 100\%$$

where: E = efficiency

a = proportion of coarse material in feed product

b = proportion of coarse material in separated tailings

c = proportion of coarse material in separated fine product (collected) (from ref. 1)

In addition to measuring classification efficiency as outlined above, the concept of protein shift as defined by Gracza[3] is of value. This is expressed mathematically as:-

$$+\delta = \frac{1}{p} \sum_{x=1}^{x=n} (px - p)\, y$$

where: δ = degree of protein shift (%)

p = protein content of parent flour (%)

px = protein content of individual fractions with higher protein level than the parent (%)

pz = protein content of individual fractions with lower protein level than the parent (%)

y = yield of individual fractions (%)

n = number of fractions produced out of the parent stock

A positive shift in protein of the parent stock into various fractions can only be accomplished at the expense of depletion of the same amount of protein from other fractions ($-\delta$).

$$-\delta = \frac{1}{p} \sum_{z=1}^{z=n} (p - pz)\, Y$$

$$+\delta \Rightarrow -\delta = \delta \text{ (degree of protein shifting).}$$

The degree of protein shift may vary from less than 5% for some conventionally milled hard wheat flours[4] to 42-45% for pin-milled legume flours.[5] Intermediate values for δ are found depending on the plant variety from which the flour was obtained, and also the severity of the milling process used to generate the flour prior to air classification.

III. AIR CLASSIFICATION OF WHEAT FLOURS

Air classification is a useful procedure for producing wheat flours with enhanced properties. However, although application of this technology is well known to the milling industry, its usage is not generally widespread.[6,7]

Some of the advantages perceived for this process[8] are the ability to produce uniform flours from wheats of varying chemical composition; the potential for blending air classification flour streams to enhance the protein content of bread flours; the development of increased absorption of bread flour by blending in about 10% of a high protein fraction; the control of granularity of flour for speciality applications in bread, cake and cookie flours; the saving of transportation costs for blending wheats and cross-shipment of flours; the manufacture of low-protein starches for various industrial starch uses and the potential for controlling the oil, ash, maltose and moisture values in the end-products. The latter point is particularly important as air-classified flours contain an average of 3% less moisture than conventionally-milled products.[9] This weight difference means higher potential yields in terms of finished products plus additional savings in transport costs between the flour mill and the bakery. Pratt[9] has observed that for each 1% difference in moisture of the flour, it is possible to add back 1.5 lbs of liquid to 100 lbs of formula without adversely affecting the appearance and other characteristics of the baked product.

In flour milling as conventionally practised, particles of wheat endosperm are gradually reduced in size by a series of smooth rolls in order that the flattened bran and germ fragments may pass over a sieve through which the flour can fall. The aperture size of the flour sieve is generally in the range 100-150 microns, although manufacture of special cake flours may involve use of extremely fine silk screens (65 microns). Wheat endosperm cells are approximately 100-150 microns in size; in milling, a large proportion of the cells are shattered and pass the screen as separated or disrupted fragments to form part of the finished flour.[4]

Wheat cells contain two distinct groups of starch granules (1) spherical or slightly polyhedral granules (1 to 10 micron diameter) and (2) lenticular granules (15 to over 40 micron diameter). Both are embedded in a protein matrix. This matrix is seen to disintegrate in the milling process into variously shaped fragments termed wedge protein.[10] This is shown diagrammatically in figure 3.

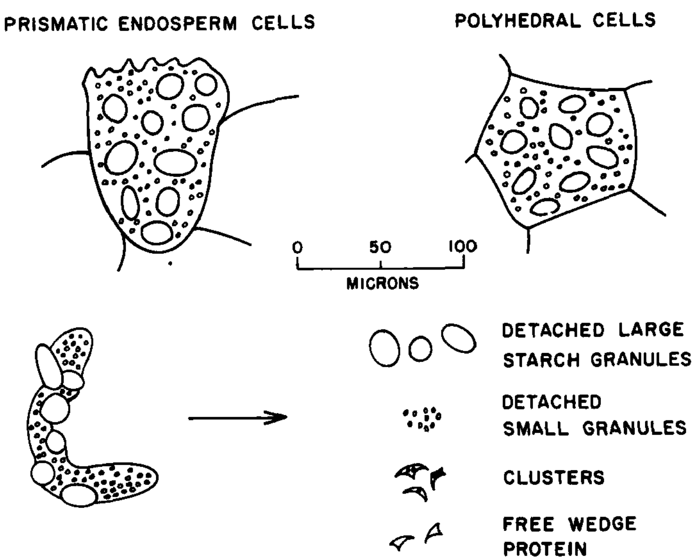


FIGURE 3

Diagrammatic presentation of wheat endosperm cells and the fragments derived therefrom in the milling process (after reference 4).

The shape and size of cells vary in different regions of the grain endosperm, the longest dimension of peripheral cells is 60 microns; that of prismatic cells is 200 microns and of central endosperm cells, 14 microns. Cell walls are 3-7 microns thick and are structurally weak. Starch granules range in size from 1-50 microns in diameter; the larger are lens shaped, the smaller spherical. These granules tend to be either large and lenticular (15-40 microns) or small and spherical (1-10 microns) in the prismatic and central cells. Those in the peripheral cells are generally intermediate (6-15 microns) in size.[11]

Flour as normally milled on roller mills consists largely of endosperm particles 2-200 microns in diameter. Those that are over 40-50 microns are generally whole endosperm cells or parts of cells; those less than 40-50 microns are starch granules, fragments of protein matrix, cell wall fragments etc. The percentage of material present in the fraction less than 40-50 microns in diameter has been termed the "degree of reduction".[12] The degree of reduction in conventionally milled flours ranges from about 10-20% for hard wheat flours to about 60% for soft wheat flours. The proportions and nature of particles from a soft wheat flour are shown in figure 4. A milled soft wheat may therefore contain about 12% by weight of particles that are 0-17 microns in diameter, with a high proportion of protein to starch. The next intermediate fraction (17-35 microns) contains more free starch and is therefore relatively low in protein content.

Individual single flour cells from winter and spring hard wheats are not as readily broken open to free starch and protein, as are the flour cells from soft wheat. In soft wheat flour, about 20% of a high protein fine fraction exists versus 15% in a hard winter wheat flour. The soft flour also contains about 60% of a fraction largely composed of free starch granules that is low in protein content. This can be compared with 25% of a similar fraction in hard winter wheat flour. The proportion of these fractions in a given wheat variety, and which are related to the degree of kernel vitreousness, varies from one crop year to another.[13]

SIZE RANGE (microns)	YIELD (% by wt.)	PROTEIN (%)	FREE STARCH GRAINS	FREE WEDGE PROTEIN	ENDOSPERM FRAGMENTS
0 - 13	4	19			
13 - 17	8	14			
17 - 22	18	7			
22 - 28	18	5			
28 - 35	9	7			
OVER 35	43	11.5			

FIGURE 4

The proportions and nature of particles milled from a soft English wheat flour (9.5% protein) - after reference 4.

Some of the problems concerning the variation in the characteristics of air classified fractions from different wheats have been reported by several authors.[4,6,13,14]

Wheat flours of varied qualities have been examined by differential sedimentation in carbon tetrachloride:benzene mixtures of density 1.44 at 20°.[15] Results from such tests may be used to demonstrate whether or not flours are suitable for fractionation by air classification. The higher the quantity of the so-called "free starch" with a maximum protein content of 2%, the more pronounced is the shift of protein level in the air-classified flours. To achieve a significant protein shift (δ) by air classification, the "free starch" collected by centrifugation in the non-aqueous solvent, density 1.44, should be 25-50% of the flour.[6] It has also been demonstrated that the small starch granules are more strongly embedded in the protein than the large granules, and can be isolated only after additional grinding of the flour in an impact mill.[4,6,8,16,17]

In a close examination of the nature of the protein of wheat flour, Hess[10] introduced the terms "wedge" or interstitial protein for the amorphous protein of the endosperm matrix, and "adhering" protein for the protein that remains on the starch granules after extensive milling. He also concluded that the adhering protein had 3-4 times more bound lipid than the wedge protein and claimed that it existed as a fibrillar network around the starch granules. Presumably a vestigial remnant of the chloroplast (granal) membrane within which the starch granule developed.[18] This is shown diagrammatically in figure 5.

The ratio of wedge protein (readily partitioned by air classification) to adhering protein (not removed by air classification) has been shown to range from 1:0.43 in German low protein soft wheats to 1:3 in high protein hard wheat varieties.[10]

This concept of the two forms of protein existing in flours derived from milled grain endosperm is supported by the observation that during grain development the starch granules are separated

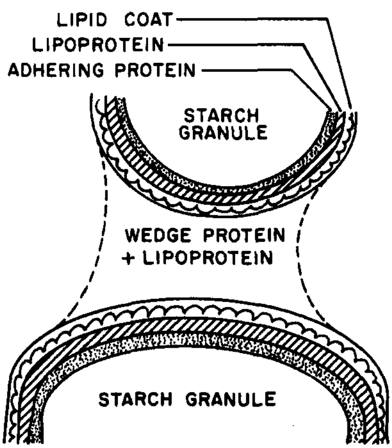


FIGURE 5

Diagram of cross-section through starch granules demonstrating configuration of wedge-protein and adhering protein (after Hess[10]).

from the storage protein by lipoprotein membranes which persist in the mature cell.[19] The storage protein is also believed to be deposited within a lipoprotein membrane in the developing endosperm.[20]

The water-soluble proteins are believed confined to a position immediately surrounding the starch granules, and this area is capable of rapid swelling upon hydration. There is also lower adhesion between the starch and protein in soft wheats, and therefore soft wheats tend to release starch granules more freely than hard wheats during milling. Fractures are found to occur around rather than through the granules with the result that there is less starch damage in milled soft wheats than that in milled hard wheat varieties.[21]

The view that a lipid-rich fibrous protein adheres to the starch granules has been challenged.[18,22] No evidence of either lipid bodies or membranes was found around the starch granules and it has been suggested that Hess's results may be an artifact. A single undifferentiated amorphous protein was found containing randomly dispersed inclusions extending up to the surface of the starch granule.[22]

The nature of the effects of fine-grinding and air classification of the high protein sub-aleurone endosperm cells of wheat has also been studied.[23] This layer lies adjacent to the aleurone layer, and differs significantly from the starchy endosperm in terms of cell size and shape, protein content, range of starch granule size etc. In some hard winter varieties the sub-aleurone has been reported to contain 31-54% protein in comparison with 8-18% in the inner endosperm.[24] In a soft winter wheat of about 8% protein, the ratio of sub-aleurone to inner endosperm is close to 2:1.[25]

It has been observed that sub-aleurone endosperm cells of high protein content tend to persist as intact cells in roller-milled and even in pin-milled flours. They therefore tend to concentrate in the coarse fraction (over 35 micron cut-size) upon air classification, and hence increase its protein content.[23] It has also been demonstrated that it is possible to separate very high protein fractions from air classified flours of particle size greater than 35 microns. Fine particles (less than 35 microns) were first removed from a commercial 3rd break flour by air classification. The sub-aleurone endosperm cells were then isolated in virtually pure intact form by sedimentation in non-aqueous solvents of suitable density. Such cells were found to contain 40-50% protein.[23] It was concluded that the process of air classification causes partial separation of the sub-aleurone from the inner endosperm. The low protein intermediate fraction (17-35 microns) is therefore depleted, and the coarse fraction (over 35 microns) is augmented with regards to sub-aleurone endosperm.

The effects of air classification of the germ of both wheat and corn have also been studied. The defatted germ has a higher concentration of protein, lipid, minerals, vitamins B and E and fiber than the endosperm. The high fiber content of the germ lowers the nutritional quality of this fraction, and attempts have been made to reduce the fiber content of defatted germ by fine milling and air classification.[26-28] This processing produces a 33% yield of a fine fraction containing about 40% protein from defatted wheat germ and 27-29% protein from defatted corn germ. Fiber contents were reduced from 2.3% and 5.7% from wheat and corn germ respectively to 0.5% or less.[28] As with wheat endosperm, the mineral content of the defatted germ was largely concentrated into the fine fraction.

The various fractions obtained by air classification of wheat have been shown to be derived from differing anatomical areas of the endosperm. There is some evidence to suggest that the protein content of these fractions varies significantly one from another in certain chemical characteristics. Concentrations of glutamic acid and proline have been found higher, but those of aspartic acid, alanine, lysine and arginine lower in the protein of subaleurone endosperm than in the protein of inner endosperm derived from hard red winter wheat. The same pattern was shown between an interstitial protein concentrate compared with an adherent protein concentrate. Starch-gel electrophoresis showed a higher gliadin-albumen ratio in subaleurone than in inner endosperm, and in the interstitial than in the adherent protein concentrate.[23] On the other hand, studies of the proteins in the fine, intermediate and coarse fractions of air classified wheat flours by fractional extraction with aqueous solvents and also ion-exchange chromatography on CM-cellulose of the gluten proteins failed to demonstrate any significant differences from the parent flour protein.[29] The only consistent variation was that the fines fraction was slightly enriched in gluten protein (acetic acid soluble). Others have shown that the different flour fractions from air classification did not show any variation in terms of content of sulphydryl and disulphide groups,[30] or in the electrophoretic characteristics of the glutens from the different fractions.[31]

The rate of gluten stretching (under constant load with an extensometer) has been found greater for glutens washed from the air classified 35-63 micron fraction, and least for those fractions with particles less than 35 microns in size.[32] However, it was suggested that such differences found in these experiments may may be due rather to the oxidation state of the fractions than to the gluten strength.

In practice, the use of air classified flour fractions does not require any major allowance for variations in baking behaviour resulting from uneven distribution of individual proteins; the overriding consideration appears to be the difference in gross protein content.

In addition to the protein displacement as evidenced above, other components are also shifted into the fines-fraction by air classification. Of particular significance is damaged starch and resultant maltose,[4,33-36] ash,[3,14,33-34,37] especially apparent in the case of air classified fines from hard wheat varieties,[36] discoloring material,[4,38] oil,[3,33,39] and vitamins such as thiamine, niacin, riboflavin, pyridoxine and pantothenic acid which are also partitioned into the fine fractions especially from hard wheat flours.[3,37,39] In addition, the enzyme lipoxygenase has been found to be concentrated into the air-classified fine fraction in some but not all varieties of wheat.[40] Whether this difference is indeed a characteristic of the different varieties tested, or rather an environmental effect on the distribution of lipoxygenase within the grain endosperm is not clear from this study. As lipoxygenases have important roles in the final color of the bread, such partitioning effects by air classification can have obvious practical consequences. The content of both reducing and non-reducing sugars have also been shown to be concentrated into the high protein fines of hard red spring wheat.[41]

Starch damage can be extremely important to the quality of flour for baking purposes. The severity of such damage depends largely on the type of wheat and severity of the milling process. The effects of various milling systems on producing starch damage have been studied;[21] and various types of mechanical damage incurred by starch granules characterized. It would appear that flour characteristics such as increased water absorption and gassing power are correlated with the type of damage that may be caused by the abrasive and flattening effects of fluted, frosted or reduction rolls used in conventional milling. Impact mills, such as pin mills, caused chipping or splitting of the starch, however, such damage was considered unlikely to exert any significant positive effects on water absorption or gassing powers. This is of relevance as impact mills are preferred for fine grinding conventionally-milled flours prior to fractionation by air classification.[16,42] This is particularly important when attempting to increase the degree of reduction of hard wheat flours due to the possibility of developing characteristics outlined above, plus the danger of fragmented starch entering the air classified fines and hence lowering its protein content.[43] Williams[21] has suggested the possibility of using air classification to remove high damaged starch granules and then to reincorporate them back into blended flours to give them enhanced effects on water absorption. This may permit the use of higher baking absorption in the recently developed short-time baking procedures.[44]

The starch isolated from the high protein containing flour fraction of pin-milled, air classified flours from varieties of hard red spring wheat show the highest pasting temperatures, highest peak height and low set-back values. This high protein fraction also contains the highest water-binding capacity values and the greatest proportion of small granules, and has the highest content of total water-solubles and water-soluble pentosans.[45] The pentosan content has also been found highest in the fine fractions of air classified corn and wheat germ flours.[27] The water solubles have been further studied,[46] and shown to contain constituents that reduced the mixing time of the extracted flour.

Thus, although it may be concluded that the protein content of the various fractions derived from air classification operations may exert their effects on product characteristics simply as a function of gross protein content rather than a result of partitioning proteins of different chemical and physical characteristics into the different fractions, the same does not appear to be the case with the carbohydrate constituents of the various air classified flours.

In order to optimize the fractionation process, attempts have been made to derive suitable conditioning treatments, and to assess their effects on the efficiency of fine grinding and air classification. Treatments such as tempering, heating, wet and dry cycles, freezing and thawing etc. on hard red winter wheats had only minor effects on the air classification response in terms of yield and protein content.[47] On the other hand, Wickser and Shellenberger[48] milled hard red winter wheat at 12, 16 and 20% moisture content and obtained 66, 72 and 64% flour yields respectively. In these experiments, the proportion of flour through a 400 mesh screen (38 microns) was 42% at 12% moisture, 32% at 16% moisture and 52% at 20% moisture.

The effects of moisture content on 5 types of wheat on the endosperm fragmentation and protein displacement has also been studied.[11] The proportion of high protein fines (0-17 microns) increased with wheat moisture content in the flours from 3 hard red winter wheats (52%, 57% and 68% yields from wheats milled at 14.7%, 17.9% and 21.3% moisture). The percentage yield of such fines decreased slightly, however, with increasing wheat moisture in the flours from the two soft wheats. The proportion of low protein intermediate flour (17-35 microns) air classified fraction in roller-milled flours from all 5 types of wheat increased when moisture contents were raised as indicated above. Marked differences were found between soft and hard wheats in their response to moisture content variations. Proportions of both fine and intermediate air classified fractions in the flour from hard wheats increased (indicating a greater degree of endosperm fragmentation) when the wheat was roller-milled at successively higher moisture contents, and also when the flour was pin-milled at successively lower moisture contents. It has also been observed that breaking of wheat at elevated temperatures also produces mealiness and softening of the endosperm, but it did not appear to affect the response of the flour to pin-milling and air-classification.[11]

The variable results achieved from air classification of flours from soft and hard wheats with and without pin-mill impact grinding are shown in Table 1.

With hard wheat flour the yield of the fine fraction is decreased, and the ratio between its protein content and that of the initial flour is reduced to about 1.5; the intermediate fraction is also decreased in yield, and its protein content shows a lower reduction than with the soft flours.

IV. PRACTICAL IMPLICATIONS OF PROTEIN DISPLACEMENT IN WHEAT GRAIN BY AIR CLASSIFICATION

As expressed earlier in this discussion, the advantage of applying air classification to wheat flours is that this technique enables the miller to "tailor-make" flours to a number of differing

TABLE I

The yields and protein contents of the three main fractions obtainable by air classification from soft and hard wheat flours with and without impact grinding (after ref. 4 & 49).

Flour	Fractions	Fraction particle size (m)	% Yield	% Protein*	Protein shift (δ)
Soft wheat	Unground flour	-	100	9.7	
		Fine (0-17 μ)	9	18.5	
		Medium (17-35 μ)	34	4.5	18
		Coarse (over 35 μ)	57	11.3	
	Impact Ground flour	Fine	20	21.9	
		Medium	68	6.6	24
		Coarse	12	10.3	
Hard wheat	Unground flour	-	100	13.1	
		Fine	3	20.2	3
		Medium	14	11.4	
		Coarse	84	13.5	
	Impact Ground flour	Fine	14	24.0	
		Medium	51	10.0	14
		Coarse	35	11.6	

* % protein : dry weight basis.

applications based on characteristics such as protein content, flour particle size, color, gassing power, water absorption etc. The process gives flexibility enabling the production of flours of consistent quality from wheats that may vary considerably in desirable characteristics from one crop year or from one geographical area to another.[50]

Numerous studies have indicated that removal of the intermediate low protein fraction (17-35 microns) from wheat flours improves the bread-making value of the remainder.[9,13,17,51,52] This low protein intermediate fraction has been found suited for speciality cake applications, e.g. conventional milling of Kansas hard winter wheat produces flour that has been shown to contain about 25% of a low protein fraction with good characteristics for cake manufacture. Removal of this 25% upgrades the quality of the balance for bread production.[13] Similarly, removing the high protein fines plus the over-sized chunks of endosperm from a soft wheat flour also yields a product upgraded for cake-making.

The utilization of this process development has been found particularly advantageous in areas of soft wheat production, such as England, France, Germany and the eastern U.S.A. where air classification has enabled the processor to upgrade the quality of the flour fractions for quality bread production.[7,53] In many parts of Europe, foreign strong wheats are taxed, thus making it economically impossible to utilize more than about 30% in the blending of wheat flours. Air classification is used to upgrade 10% protein wheat flours up to 12% protein flours. The process yields considerable quantities of low protein wheat flour (5% protein) some of which is utilized for cake flour processing, the bulk being used as a brewing adjunct.[53,54]

In the United States, the early 1960's witnessed several years where inferior quality hard winter wheats were harvested. Air classification multi-unit installations were seen as a practical means of overcoming these inadequacies. The problem has, however, been largely resolved in recent years by the introduction of new improved strains of wheat.[7]

Paradoxically, during this same period, the soft wheat growing areas of the eastern USA were faced with an undesirable increase in the protein content of their soft wheats - probably a result of increased usage of chemical fertilizers. The effect of this development was to force processors to purchase low protein wheats, often at higher prices, for blending to produce low protein cookie and cake flours. This phenomenon led to several successful installations of air classification operations[7] to produce cake and cookie flours (very low protein) and pretzel and cracker flours (medium protein, coarse flours).

Due to the characteristics of soft wheat flour there is generally no need to utilize impact grinding systems; use of such rigorous milling procedures, particularly beneficial when processing hard wheat flours, involve extra cost factors. Grinders and classifiers require about 100 H.P. per long ton per hour capacity for processing hard vitreous wheats.[55] Commercial classifiers operating at cut sizes from 8 to 60 microns are capable of feed rates from 1000 to 6000 kg/hour. These operating costs combined with capital investment and overheads can make the process of air classification run high. Its application can therefore only be warranted where the value-added potential more than compensates for these additional processing costs.

V. APPLICATION OF AIR CLASSIFICATION TECHNIQUES TO CROPS OTHER THAN WHEAT

The degree of protein shift produced by partition in an air stream has been used as an indicator of the degree of "softness" of a wheat flour.[3] There is, considerable variation in the percentage protein shift within different wheat varieties, for example, with δ = 5-8% for conventionally milled hard English wheats; 16-21% for soft English wheats.[4] This variation in degree of protein shift is even greater when other grains, tubers and grain legumes are subjected to fractionation by fine milling and air classification as shown in Table II.

TABLE II

Protein shifts produced by air classification of flours from barley, oats, Triticale, rice, potato, peas and beans.

Flour	% Protein shift (δ)	Reference
Barley (roller milled)	19	56
Barley (pin milled)	28	57
Malted barley (milled & screened)	8	58
Malted barley (pin milled)	18	57
Oats (pin milled)	27-32	57
Triticale (pin milled)	28-36	60
Rice (turbo-milled)	8-10	61
Potato (pin milled)	22-25	62
Field peas (pin milled)	42	5
Horsebeans (pin milled)	45	5
California white beans (turbo-milled)	22	63

1. Barley and Malted Barley

The air classification of barley flour produces both protein-enriched and low-protein starch streams in yields of 17.5% (30.0% protein, dry basis), and 82.5% (9.3% protein) respectively.[57] Maximum starch recoveries of 44% from barley flour have been obtained by alkaline washing of the air classified coarse fractions.[64] When conventionally milled barley flours are subjected to fractionation by air classification,[56] a lower percentage protein shift is obtained than with impact milled flours (Table II). Roller milled barley flour (65% milling extraction) produced approximately 40% yields of an intermediate particle size fraction with a protein content of 7.25%. This fraction was tested as a brewing adjunct and found satisfactory;[56] however, the feasibility of using such fractions will depend on the markêtability of the protein-enriched fractions and also because of the fine nature of these flours on overcoming the practical problems of filtering rather than the traditional lautering of the mash. The concept of utilizing these protein-enriched fractions of barley is being evaluated in Europe, as a means to decrease dependency on costly soybean imports for animal feed (F. Holm, Kolning, Denmark; private communication).

Commercial malt flours have been fractionated by both screening and air classification, but little significant degree of protein shift was achieved.[58] However, when malt barley is coarse ground and the fiber removed by appropriate screening operations, the flours obtained in approximate 77% extraction yield, can be fine milled and air classified to produce coarse, low protein, starch-rich fractions in about 85% yield.[57] Successful utilization of such products by the brewing industry would depend on the factors as outlined above for the barley adjuncts. The protein-enriched fractions from malt may, however, be more acceptable to the food industry than similar fractions from barley, due to the desirable flavor and color characteristics of the former flour.

2. Oats

Oat groats as well as first and second roller milled oat flours can be fine ground and air classified to yield fractions ranging in protein content from 4-88%.[59] The production of a very high protein fine fraction containing 83-88% protein (in 2-5% yield) is apparently unique to oats, and has not been previously observed for wheat, rye, corn, sorghum or triticale flours. This fraction accounts for 14, 16 and 7% respectively of the total protein in first and second flours and groats. The next fraction (25-29% by weight) with 15-39% protein accounted for 38-48% of the total protein for the flours.

3. Triticale

This grain is a man-made hybrid between wheat (Triticum) and rye (Secale). Triticale flours have lower mixing strength and loaf volumes than from doughs prepared from bread wheat flours. Air classification of pin-milled flours gave a high percentage protein shift (28-36%)[60]. Yields obtained of the low protein, starch fractions were found similar to soft wheat, but higher than from rye or hard wheat. More protein was found in the triticale fine fractions than in those from soft wheat flours, although the yield of these fractions were similar to the soft wheats.

4. Rice

Rice protein has a high nutritional value and modern varieties contain 9-11% protein, mostly concentrated into the outer kernel layers. Recovery of this protein by fine grinding and air classification has been studied.[61,62,65,66] In general, poor protein shifts were experienced, and use of fine grinding techniques decreased rather than increased the degree of shift, presumably due to increased starch damage. It has been recommended that abrasive milling processes may be more attractive, as its scouring action would effectively recover an enhanced protein fraction with little extra cost over the usual rice milling operation.[61]

Air classification of defatted rice bran or polish has been shown to produce enriched protein contents in some of the fractions, but likely not significant enough to be useful.[65] Similar studies in our laboratory demonstrated a 50:50 split between the coarse and fines of classified pin milled defatted rice bran with the former containing 14% crude fiber and the fines about 2% crude fiber (Vose, unpublished data).

5. Sorghum

A considerable amount of grain sorghum is dry-milled in the USA much going to brewers grits and aluminum ore refining, as well as pet food grist, paper making, charcoal briquets and oil well drilling. Studies have indicated that sorghum flours respond like wheat flour to air classification,[67] with production of a 40% yield of sorghum flour with less than 5% protein suited to many industrial applications.[68]

6. Potatoes

It has been demonstrated that potatoes can be processed to produce a fine flour that is amenable to protein displacement by air classification.[62,69] Pin-milled dried potatoes can be classified to yield 13% of a 17.3% protein fine fraction, and 87% containing 6.3% protein. The protein content of this coarse fraction can be further reduced to 4% by sieving the pin-milled flours over 125 micron screens prior to air classification (obtained in 67.5% yield). The balance containing 13.7% protein could be channelled into feed markets.[62] Higher yields (90%) of lower protein (2.5% protein) starch flours have been reported.[69] However, such fractionations necessitated spray drying of the cooked potato mash which may be economically impractical. The economies of such dry processing techniques would have to be related to the costs of recovery of potato starch by the traditional wet milling operations which have the additional disadvantage of requiring effluent disposal facilities with associated high costs.

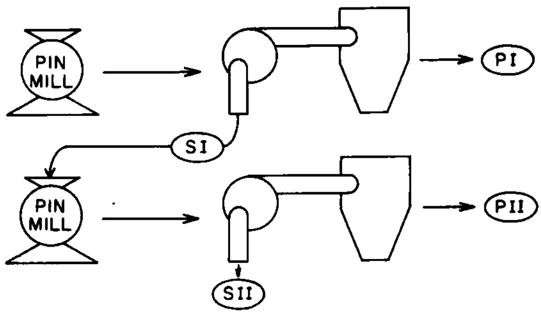
7. Grain Legumes

An interesting recent development concerning applications of fine grinding and air classification is seen in the effect of these techniques on the protein shift in flours derived from field peas and horsebeans.[5] Due largely to the content of fairly uniform large diameter starch granules (approx. 25-40 microns) compared to the mixed populations of small and medium-sized granules in most cereal grains, these legume flours are amenable to fractionation into high protein (approx. 60%) and low protein (approx. 4-5%) flours by air classification. The data in figure 6 indicates a schematic flow sheet for dry processing of field peas and horsebeans. Protein shifts of 40-45% are encountered in dry processing these legume flours. Combining the two protein fractions obtained from two passes through the pin mill and the air classifier produces a 44% yield of a 57% (dry basis) flour from field pea flour containing 28.8% protein. A 42% yield of a 61%

(dry basis) flour is obtained from horsebeans containing 31.9% protein.[5] Lesser efficiencies of protein shift have been reported with California small white beans.[63] Hull fiber present in these flours is dense in nature and tends to be concentrated into the coarse starch fraction.

The starch concentrates contain about 4-5% protein, most of which can be readily removed if necessary by further wet processing. The nature of the residual adhering protein on the legume starch granules has been described.[70] The starch-rich fraction from repeatedly milled and air classified green field pea flours was observed to be green in color. The green membrane fraction was isolated from the starch granules and found to contain 50% protein, 30% lipid and a high chlorophyll content. The protein-rich fraction from air-classification of these flours was off-white in color. Proteins from these starch-bound membranes were shown to be distinct from the protein of the fine protein-enriched flours by virtue of their different amino acid analyses, polyacrylamide gel electrophoretic patterns and nitrogen solubilities. This is of interest as it tends to support other work in which the amino acid composition of adherent protein was also found different to that of intestitial protein in wheat flours[23].

This process technology is of value to locations where climate and other agronomic conditions preclude the production of soybeans. In such areas (e.g. temperate locations of Europe and the Canadian Prairies), field peas and numerous bean varieties give good yields, and application of dry milling techniques may provide the means of manufacturing protein-enriched flours to compete with imported soybean products. The starchy flours derived from the air classification process in a Canadian operation have been utilized in a variety of industrial applications such as potash ore refining, adhesives for corrugated board production, and manufacture of pressure-sensitive microcapsule coatings for carbonless paper[71].



PEAS

	WHOLE SEED			DEHULLED SEED	
FLOUR	100 lbs		(25.7% protein)	100 lbs	(28.8% protein)
SI	75 lbs	"STARCH"	(13.3% protein)	69 lbs	(14.5% protein)
PI	25 lbs	"PROTEIN"	(63.5% protein)	31 lbs	(60.5% protein)
SII	56 lbs	"STARCH"	(5.6% protein)	52 lbs	(4.8% protein)
PII	19 lbs	"PROTEIN"	(48.3% protein)	17 lbs	(40.0% protein)

HORSE BEANS

	WHOLE SEED		DEHULLED SEED	
FLOUR	100 lbs	(27.9% protein)	100 lbs	(31.9% protein)
SI	72 lbs	(15.1% protein)	70 lbs	(16.5% protein)
PI	28 lbs	(66.1% protein)	30 lbs	(69.0% protein)
SII	58 lbs	(5.2% protein)	52 lbs	(4.2% protein)
PII	14 lbs	(51.1% protein)	18 lbs	(49.6% protein)

FIGURE 6

Schematic flowsheet for dry processing of field peas and horsebeans.

The technical feasibility of this process has been proven, but the continued success of applying air classification procedures to fractionating grain legume flours on a commercial scale will depend on the ability to compete economically with soybean derived protein-flours and also starches from wheat or corn processing.

VI. CONCLUSION

Protein displacement by application of air classification techniques to cereal grain flours produced by either conventional milling or by fine impact milling procedures have been shown to produce wheat flours with enhanced properties for a range of applications. Classifiers are commercially available that can provide extremely fine and reproducible cut-points to yield a range of protein shifts depending on the physical nature of the flour to be processed and the plant source from which the flour was obtained. Protein shifts range from a low value (less than 10%) in the case of rice and certain hard wheat flours to a high level (over 40%) in certain grain legume flours.

The advantages of dry processing of flours by air classification include cost benefits as there is no need for costly drying processes and effluent disposal systems as evidenced in wet processing plants. There is also the advantage of increased flexibility to the processor in that a variety of flours suited to a number of different applications can be manufactured from a single seed source. Such advantages have to be weighed against the increased capital and operating costs in the utilization of these techniques.

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