CHAPTER TWELVE

Rapeseed and Mustard

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The two rapeseed species *Brassica napus* L. and *B. campestris* L., together with the mustard species *B. juncea* (L.) Czern., are commonly referred to as the oilseed brassicas. Collectively, they occupy over 13 million ha and provide more than 12% of the world’s edible oil. In the period 1975 to 1985, *Brassica* oil production and use has increased faster than that of any other oil crop, except the oil palm (*Elaeis* spp.).

Oilseed brassicas are well adapted to cool, moist growing conditions and require fewer heat units than soybean [*Glycine max* (L.) Merr.] or sunflower (*Helianthus annuus* L.). They are cultivated as cool-season crops in the subtropics and as winter annuals in the milder regions of the temperate zones. At higher elevations and at the extremities of the temperate regions, they are grown as spring-sown crops. Major oilseed *Brassica*-producing regions include China, Canada, the Indian subcontinent and northern Europe (Table 12-1).

The small, round *Brassica* seeds contain 40 to 44% oil on a dry-weight basis and produce an oil-free meal with 38 to 41% protein. In many Asian countries, the meal is utilized as an organic fertilizer, but in the western world, it is used exclusively as a high-protein feed supplement for livestock and poultry.
Table 12-1  Brassica Oilseed Production by Region for the Period 1962–1963 through 1982–1983

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Canada</td>
<td>210</td>
<td>1970</td>
<td>2250</td>
</tr>
<tr>
<td>China</td>
<td>1040</td>
<td>1220</td>
<td>5660</td>
</tr>
<tr>
<td>Indian subcontinent</td>
<td>1190</td>
<td>1650</td>
<td>1150</td>
</tr>
<tr>
<td>Northern Europe</td>
<td>370</td>
<td>960</td>
<td>2620</td>
</tr>
</tbody>
</table>

**TYPES OF CULTIVARS**

**Mode of Propagation**

The inflorescence of the brassicas is racemose, and flowering is indeterminate beginning at the lowest bud on the main raceme. (Fig. 12-1). Flowering on secondary branches begins 3 to 5 days after the first flowers have opened on the main raceme. The stigma is normally receptive for approximately 3 days before and 3 days after the flower opens.

The flower is radial with four sepals alternating with four petals forming the typical cross pattern from which the Cruciferae family derives its name. The petals are normally pale yellow, but variation from dark yellow to almost white has been observed. Several genes have been reported to affect flower color (Pearson, 1929; Anstey, 1955; Sernyk and Stefansson, 1982). The two lateral stamens are shorter and remain introrse while the four longer median stamens, although introrse in the bud, gradually become extrorse as the flower opens. This arrangement is similar in all Brassica species except yellow sarson, a self-fertile, Indian subspecies of B. campestris, in which all the stamens remain introrse.

B. napus and B. juncea are mainly self-pollinating, although under field conditions an average of 30% outcrossing occurs, depending on wind and bee activity (Rakow and Woods, 1987). In contrast, most B. campestris ecotypes are self-incompatible (Richards and Thurling, 1973). The self-incompatibility is of the homomorphic, sporophytic type controlled by a series of S alleles (Bateman, 1955). In its most simplified form, the presence of the same S allele in the pollen and stigma will inhibit germination of the pollen grain or prevent the pollen tube from penetrating the stigmatic surface.

Ito (1981) reviewed the many techniques devised to overcome this natural barrier to self-fertilization. Bud pollination (Sampson, 1962) before the inhibitory process is activated in the stigma, or the exposure of
plants or flowers to high atmospheric CO₂ levels following pollination (Nakanishi and Hinata, 1973), are among the procedures successfully applied. Some self-incompatible lines have been found in *B. napus* (Olsson, 1960). In *B. campestris*, self-compatible lines, such as the Indian yellow sarson types, also occur.

After fertilization, which is usually complete within 24 hours of pollination, the syncarpous ovary elongates to form a pod (silique). The pod generally has two carpels separated by a false septum. Because each pod may contain 25 or more seeds and each plant produces many pods,
the multiplication rate per generation usually exceeds 1000 to 1, thereby accelerating the breeding and evaluation processes.

The developing seeds are green, but the embryos lose their green color and become bright yellow as they approach physiological maturity. Simultaneously, the seed coat turns black, reddish brown, or remains translucent depending on the genotype of the plant. The seed coat consists of an outer epidermis, a single row of palisade cells and a thin layer of crushed parenchyma. The palisade cells may differ in length resulting in reticulations on the seed surface that are characteristic for each species (Vaughan, 1970). At maturity, the embryo represents approximately 85% of the seed weight, with the single, thin layer of endosperm and the testa making up the remainder. The cotyledons, unlike those of beans or alfalfa, are conduplicate, with the larger outer cotyledon folded over the inner cotyledon. The cotyledons enclose a small plumule and attach to the short radicle. At maturity, the seeds are nearly round and weigh from 2 to 5 mg depending on the species and form.

Cultural practices used in the production of Brassica crops vary greatly. In western countries, the crop is normally sown in drill rows at a seeding rate of 5 to 8 kg/ha. On the Indian subcontinent, the seed is usually broadcast on the soil surface and buried by drawing a heavy plank over the fields. In China, the crop is sown in starter beds containing a dense stand of seedlings which are later transplanted into recently harvested rice fields.

To ensure a uniform stand, the small-seeded Brassica species should be sown into firm, moist soil to a depth of not more than 2 to 3 cm. Under favorable growing conditions, the seedlings will emerge within 4 to 5 days. Cotyledon expansion is quickly followed by the growth of a rosette of true leaves.

There are both winter and spring (summer) forms of B. napus and B. campestris. In B. juncea, only the summer form has evolved. The winter form of B. napus is dominant in northern Europe, China, northwest United States, and some South American countries, such as Chile. The winter form is sown in the fall (early to late August in Europe), so that five to eight true leaves are formed before winter. The crop remains in the rosette stage until spring. In cultivars with strong winter hardiness, a period of approximately 40 days at near freezing temperatures is required to effect vernalization (Andersson and Olsson, 1961).

The winter form of B. campestris is grown only to a limited extent, because its seed and oil yield is less than the winter form of B. napus. However, the greater winter hardiness and shorter growing season of B. campestris makes it a suitable crop for the more severe climates of Sweden and Finland. The winter forms of both species are less winter hardy than winter wheat, but more hardy than winter barley.
The spring form of *B. napus* is normally sown in April to May, flowers in July and is harvested in late August or early September. In Canada, northwest China, Denmark, and parts of Sweden, the spring form of *B. napus* dominates. However, in most European countries, the spring form generally is used only to reseed winter fields that have not survived the winter.

In western Canada, parts of Sweden and Finland, as well as northwest China, the spring form of *B. campestris* is grown extensively. It is sown in April or May, flowers in June and is harvested in August. Although it produces lower oil and seed yields than other oilseed brassicas, its short growing season of 80 to 95 days and its high tolerance to spring frosts make it well adapted to production in these climates.

On the Indian subcontinent, *B. campestris* and *B. juncea* are important. The *B. campestris* species is normally grown in the September through December period while *B. juncea* dominates in the November to April growing season.

The length of time the crop remains in the rosette stage can vary from less than 30 to more than 210 days depending on climatic conditions and the species and form grown. Exposure to long days and rising temperatures result in floral initiation and rapid bolting. Growth stages for the spring form of both *B. campestris* and *B. napus* have been defined and illustrated (Harper and Berkenkamp, 1975).

**Past and Current Cultivar Types**

Centuries of rapeseed cultivation in Europe led to the development of local landraces of both *B. napus* and *B. campestris*. The *B. napus* species was favored for production on good soil and under favorable growing conditions, while *B. campestris* was preferred for lighter soils and more harsh climates. Landraces formed the basic breeding materials used by the first farmer-breeders. In the early years, the most important characteristic under selection was winter hardiness. The first European winter rapeseed cultivar released was called ‘Lembkes,’ a *B. napus* selection developed in Germany in the early twentieth century. This cultivar was extensively used in breeding programs of other countries, such as Sweden, France and Poland.

On the Indian subcontinent, oilseed production from *B. campestris* and *B. juncea* is mentioned in the early Sanskrit writings of 2000 B.C. Over the centuries, three *B. campestris* ecotypes evolved:

*B. campestris* L. ssp. *oleifera* var. yellow sarson includes yellow sarson or yellow seeded Indian colza.
B. campestris L. ssp. oleifera var. brown sarson includes brown sarson types variously referred to as Kanpur lotni or toria brown sarson and other local names.

B. campestris L. ssp. oleifera var. toria includes the toria types, such as brown toria, yellow toria, lahia or toria Abohar (Prakash and Hinata, 1980).

One B. juncea ecotype locally known as rai also is grown. Traditionally, rai and the sarsons have been sown in October or November and harvested in March or April, while toria is grown September through December. Breeding of improved rape and mustard cultivars for India began as early as 1910, at Lyallpur in the Punjab. Breeding programs established at several additional centers have resulted in the development of several improved B. campestris and B. juncea cultivars.

In Canada, rapeseed production began in the early 1940s with the introduction of B. napus seed from Argentina. Although the true origin of this seed was almost certainly European, the term "Argentine-type rapeseed" usually is applied to this species in Canada. Seed of spring B. campestris was introduced into Canada from Poland by a farmer and is commonly referred to as Polish or turnip rape. Both introductions were highly heterogeneous and formed the basis for future cultivar development. The most important breeding objectives were improvement of seed and oil yield. In B. napus, selection for earlier maturity also was required while the early maturing B. campestris species was well adapted to northern, short growing season areas.

In the short time since the initiation of Canadian rapeseed breeding programs, a succession of cultivars that combine superior seed yield and increased seed oil and oil plus protein content, with nutritionally superior oil and meal quality, have been released (Tables 12-2 and 12-3). The elimination of nutritionally undesirable components—erucic acid (C22:1) from the seed oil and sulfur-containing glucosinolates from the meal—has greatly expanded the market for both the seed and its products. In western Europe, these improved nutritional characteristics had to be transferred from the spring forms to adapted winter cultivars. Low-erucic, low-glucosinolate European winter rapeseed production is expected to begin in 1991.

A computerized listing of old and new rapeseed cultivars and their origins is maintained by Dr. L. Sernyk of Continental Grain, Winnipeg, Manitoba, Canada.

EXTENT AND NATURE OF BREEDING PROGRAMS

European rapeseed breeding started in the early years of this century in Germany and the crop has been bred continuously since that time. The


### Table 12-2 Performance of Canadian B. napus Cultivars in Western Canada

<table>
<thead>
<tr>
<th>Year Released</th>
<th>Cultivar</th>
<th>Seed Yield*</th>
<th>Days to Mature</th>
<th>Percent Oil†</th>
<th>Percent Protein‡</th>
<th>Seed Quality§</th>
</tr>
</thead>
<tbody>
<tr>
<td>1943</td>
<td>‘Argentine’</td>
<td>100</td>
<td>101</td>
<td>40.5</td>
<td>47.1</td>
<td>HE HG</td>
</tr>
<tr>
<td>1954</td>
<td>‘Golden’</td>
<td>101</td>
<td>101</td>
<td>41.1</td>
<td>43.9</td>
<td>HE HG</td>
</tr>
<tr>
<td>1963</td>
<td>‘Tanka’</td>
<td>106</td>
<td>101</td>
<td>42.7</td>
<td>46.3</td>
<td>HE HG</td>
</tr>
<tr>
<td>1966</td>
<td>‘Target’</td>
<td>109</td>
<td>99</td>
<td>43.9</td>
<td>45.4</td>
<td>HE HG</td>
</tr>
<tr>
<td>1970</td>
<td>‘Turret’</td>
<td>111</td>
<td>98</td>
<td>44.5</td>
<td>45.4</td>
<td>HE HG</td>
</tr>
<tr>
<td>1968</td>
<td>‘Oro’</td>
<td>107</td>
<td>106</td>
<td>41.7</td>
<td>43.4</td>
<td>LE HG</td>
</tr>
<tr>
<td>1973</td>
<td>‘Midas’</td>
<td>118</td>
<td>98</td>
<td>43.8</td>
<td>42.9</td>
<td>LE HG</td>
</tr>
<tr>
<td>1974</td>
<td>‘Tower’</td>
<td>112</td>
<td>97</td>
<td>42.6</td>
<td>47.2</td>
<td>LE LG</td>
</tr>
<tr>
<td>1977</td>
<td>‘Regent’</td>
<td>115</td>
<td>98</td>
<td>43.1</td>
<td>47.0</td>
<td>LE LG</td>
</tr>
<tr>
<td>1981</td>
<td>‘Andor’</td>
<td>119</td>
<td>95</td>
<td>43.6</td>
<td>45.9</td>
<td>LE LG</td>
</tr>
<tr>
<td>1982</td>
<td>‘Westar’</td>
<td>127</td>
<td>95</td>
<td>44.3</td>
<td>46.0</td>
<td>LE LG</td>
</tr>
</tbody>
</table>

* Seed yield expressed as a percentage of the cultivar ‘Argentine.’
† Oil content expressed as a percentage of moisture-free seed.
‡ Protein content expressed as a percentage of moisture- and oil-free meal.
§ H = high; L = low; E = erucic acid; G = glucosinolate.

Swedish programs were initiated some 40 years ago, while those in France and Poland came later. In Britain, oilseed rape breeding began in the mid 1970s when rapeseed became a major crop in that country.

Today, many private European breeding firms, together with publicly funded research institutions, are involved in rapeseed breeding and related agronomic research. In France, the Station d’Amelioration des

### Table 12-3 Performance of Canadian B. campestris Cultivars in Western Canada

<table>
<thead>
<tr>
<th>Year Released</th>
<th>Cultivar</th>
<th>Seed Yield*</th>
<th>Days to Mature</th>
<th>Percent Oil†</th>
<th>Percent Protein‡</th>
<th>Seed Quality§</th>
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<td>‘Polish’</td>
<td>100</td>
<td>88</td>
<td>40.5</td>
<td>43.6</td>
<td>HE HG</td>
</tr>
<tr>
<td>1964</td>
<td>‘Echo’</td>
<td>112</td>
<td>90</td>
<td>40.8</td>
<td>43.7</td>
<td>HE HG</td>
</tr>
<tr>
<td>1969</td>
<td>‘Polar’</td>
<td>109</td>
<td>89</td>
<td>42.3</td>
<td>44.2</td>
<td>HE HG</td>
</tr>
<tr>
<td>1971</td>
<td>‘Span’</td>
<td>109</td>
<td>87</td>
<td>39.6</td>
<td>42.8</td>
<td>LE HG</td>
</tr>
<tr>
<td>1973</td>
<td>‘Torch’</td>
<td>111</td>
<td>87</td>
<td>40.1</td>
<td>43.2</td>
<td>LE HG</td>
</tr>
<tr>
<td>1977</td>
<td>‘Candle’</td>
<td>103</td>
<td>87</td>
<td>42.1</td>
<td>43.2</td>
<td>LE LG</td>
</tr>
<tr>
<td>1981</td>
<td>‘Tobin’</td>
<td>110</td>
<td>87</td>
<td>42.5</td>
<td>43.2</td>
<td>LE LG</td>
</tr>
</tbody>
</table>

* Seed yield expressed as a percentage of the cultivar ‘Polish.’
† Oil content expressed as a percentage of moisture-free seed.
‡ Protein content expressed as a percentage of moisture- and oil-free meal.
§ H = high; L = low; E = erucic acid; G = glucosinolate.
Plantes de Rennes (INRA) is responsible for breeding and agronomic research work in rapeseed. Ringot, a private firm, collaborating closely with the INRA station, has bred high yielding cultivars, such as 'Jet Neuf' and 'Bienvenue.' In Germany, rapeseed breeding is carried out by several small private breeding companies of which the Lembke plant breeding firm has the longest history. The Institute for Plant Breeding at the University of Göttingen, as well as the Plant Breeding Institute at the University of Giessen, are the leading West German institutions specializing in breeding for quality, while several other institutions are working on various aspects of rapeseed diseases, pests, and biotechnology techniques.

In Sweden, unlike most other western European rapeseed-producing countries, the spring and winter forms of both rapeseed species are bred (Olsson, 1978). Svalof A.B., also known as the Swedish Seed Association, has a long history of rapeseed breeding, having produced the winter *B. napus* cultivars 'Matador,' 'Panter,' and 'Norde.' Svalof has been a leader in breeding for improved quality of rapeseed oil and meal. Recently, the Weibull breeding firm at Landskrona, Sweden, has initiated a rapeseed breeding program, as has the Plant Breeding Institute at Cambridge and Nickerson RPB at Rothwell, England. In Poland, the breeding work of several centers is coordinated through the Oilseed Department of the Plant Breeding Institute in Poznan.

The first rapeseed breeding program in North America was established as a war measure in 1943 at the Dominion Forage Crops Laboratory, Saskatoon, Canada, a forerunner of the Agriculture Canada, Saskatoon Research Station. At that time, rapeseed oil was an essential lubricant for steam-powered ships and locomotives because high erucic rapeseed oil clings to steam and water-washed surfaces better than any other oil. With European and Asian rapeseed supplies cut off by the war, western Canada undertook to produce the required commodity to keep the allied navies operating. It soon became evident that the spring forms of *B. napus* and *B. campestris* were well suited to northern prairie cropping systems and that the opportunities for edible oil applications was much greater than the industrial oil market. Following the war, a rapeseed export market was established in Japan, where rapeseed oil is prized as a premium cooking oil. This and other export markets provided a production base upon which the domestic edible oil market was developed.

As the economic importance of the crop increased, breeding programs were established by the Plant Science Departments at the University of Manitoba, Winnipeg, in 1953, and the University of Alberta, Edmonton, in 1969, in addition to the existing program at Saskatoon. Other publicly supported programs were initiated in the early 1980s at the Crop Science Department, University of Guelph in Ontario, and the Agriculture Canada, Beaverlodge Research Station in northern Alberta.
The possibilities of developing hybrid cultivars and successfully applying biotechnology in the oilseed brassicas has attracted the interest of several North American biotechnology and breeding firms, including Allelix in Mississauga, Ontario; the Alberta Wheat Pool and Biotechnica International of Canada in Calgary, Alberta; Continental Grain Canada in Winnipeg; Paladin Hybrids Inc., Brampton, Ontario; Calgene in Davis, California; Agrogenetic, Madison, Wisconsin; and others.

The major emphasis of public breeding programs has been the development of superior cultivars of spring *B. napus* and to a lesser extent, *B. campestris*. Research on *B. juncea* has been largely limited to Saskatoon. Work on winter *B. napus* is presently conducted at the University of Guelph, at Allelix and at the University of Idaho, Moscow in the United States.

On the Indian subcontinent, the Indian Council for Agricultural Research supports rapeseed and mustard research programs at the genetics division of the Indian Agriculture Research Institute in New Delhi and many provincial universities. The largest programs are centered at Haryana Agricultural University at Hisar and the G. P. Pant University at Pantnagar. The main program in Pakistan is located at the Pakistan Agricultural Research Center in Islamabad, but each province also has a rape and mustard improvement program.

There are many rapeseed programs in China with the major centers at the Shanghai Academy of Agricultural Sciences, Shanghai; the Institute of Oil Crops Research, Wuhan; Jiangsu Academy of Agricultural Sciences, Nanjing; the Qinghai Academy of Agricultural Sciences, Qinghai; the Central China College of Agriculture, Wuhan and many other provincial colleges and institutes.

In Australia, *Brassica* oilseed research is conducted by the states of New South Wales, Victoria and Western Australia, the Commonwealth Scientific and Industrial Research Organization, and Pacific Seeds, a subsidiary of Continental Grain.

No international research centers have been established for oilseeds, such as exist for wheat, rice, and several other important crop plants. However, the Groupe Consultatif International de Recherche sur le Colza in Paris, France, serves as a clearinghouse for scientific information on rapeseed and organizes international congresses every 4 years.

**BREEDING OBJECTIVES FOR CULTIVAR DEVELOPMENT**

In the early years of *Brassica* oilseed breeding, the major objectives were to improve the agronomic performance of the crop. The need to improve the nutritional qualities of rapeseed oil and meal was recognized in the
late 1940s, but it was not until the late 1950s that fast and accurate methods required to measure the important oil and meal constituents could be developed.

Agronomic Traits

*Seed Yield.* Seed yield, which is probably the most difficult and expensive trait to accurately measure, remains the major objective of most breeding programs. A low-yielding cultivar will not succeed unless the market or a government is willing to compensate the grower for the yield differential. However, yield cannot be the sole criterion. Late-maturing strains frequently produce higher seed yields, but may also increase the risk of frost, drought, or heat damage to an unacceptable degree. Similarly, the market may discriminate against a high-yielding cultivar due to its lower oil content or tendency to retain significant levels of chlorophyll in the mature seed. In the subsistence agriculture practiced in much of the Indian subcontinent, a cultivar with the ability to give a consistent yield under variable climatic conditions is preferred to a cultivar that has the potential for outstanding yields only under favorable growing conditions.

*Winter and Frost Hardiness.* The degree of hardiness required in winter forms varies with the production region. The mean survival rate of a rapeseed cultivar should be at least 95% over several years and locations within the proposed production region. Excessive vernalization requirements could result in a delay or failure of the crop to initiate flowering. It is also important that the cultivar has a strong capability to regrow and produce a crop even though it has sustained heavy damage during the winter. In general, the ability of winter *B. napus* and *B. campestris* to compensate for stand reduction is much greater than that of winter cereals.

Although the ability of a spring rape cultivar to withstand several degrees of frost at flowering is important in Sweden and India, it is not a major breeding objective. There is evidence that measurable differences in frost tolerance exist between Swedish and Indian materials (Aberg, 1984).

*Disease Resistance.* Numerous fungi, mycoplasms, and viruses are pathogenic to the oilseed brassicas. Fortunately, resistant cultivars can be developed for many of these pathogens.

Blackleg, *Leptosphaeria maculans* (Desm.) Ces. and de Not., also known as *Phoma lingam* in its imperfect stage, is one of the most severe
diseases attacking *B. napus* and *B. campestris*. Most *B. juncea* strains and cultivars are resistant in both the seedling and mature plant stages. Single isolates of the organism do not produce pseudothecia, but when isolates from Canada, Australia and England were crossed, fertile pseudothecia were produced, indicating heterothallism in this pathogen (Petrie and Lewis, 1985). Thus, it is very important that isolates from geographically distant sources not be transferred among regions on seed or by other means, because genetic recombination may occur and result in an increased pool of virulence genes. Blackleg infections can occur through both pycnosporos and ascospores. The mycelia grow into and can completely girdle the stem, resulting in yield losses due to premature ripening and lodging. Fungicide control is not economic in the winter forms which have a long period of exposure to infection by ascospores in the fall and pycnosporos in the summer, but fungicidal control may be feasible in spring-sown crops where the infection period is short. The ultimate breeding objective is to incorporate resistance genes into superior cultivars from sources already identified in both spring and winter forms (Kolte, 1985).

*Sclerotinia sclerotiorum* (Lib.) de Bary poses an equal or even greater threat to all brassicas than blackleg. Because of the pathogen’s wide host range, it is unlikely that resistant cultivars can be selected, although some rape strains have been observed to have greater tolerance than others (Kolte, 1985). Infection occurs during the flowering period with only the aerial parts of the plant being infected by ascospore discharge from apothecia germinating on the soil surface. It has been observed that cultivars that lodge tend to create more humid conditions at the soil level, thus favoring apothecia germination and spore dispersal, which frequently results in an elevated incidence of the disease in lodged crops. It has been suggested the development of cultivars with fewer basal leaves or leaves with a deeply lobed blade might result in reduced humidity levels and, thus, suppress spore production and discharge within the crop canopy. Apetalous mutants may provide another means of reducing sclerotinia infection because infected petals, which fall to the leaves after flowering, serve as an ideal medium for the germination of spores before the mycelia penetrate the leaf and stem. However, until resistant germplasm has been identified or the effectiveness of avoidance mechanisms demonstrated, fungicide treatment at flowering seems to be the only effective control measure.

White rust, *Albugo candida* (Lev.) Kunze, causes economic losses in *Brassica* oilseeds when it attacks and deforms the floral parts. Races of white rust that attack *B. campestris* (race 7) and *B. juncea* (race 2) have been identified (Pound and Williams, 1963; Pidkalny and Rimmer, 1985). European and Canadian *B. napus* cultivars are resistant to all
known races of white rust, but many Chinese cultivars are susceptible to race 7 (Fan et al. 1983). It is believed that in attempts to develop adapted forms of the introduced B. napus species, early Chinese breeders made interspecific crosses with the susceptible, indigenous B. campestris populations, thus transferring susceptibility to white rust into B. napus.

The first white rust-resistant B. campestris cultivar ‘Tobin,’ derived from crosses with resistant Mexican materials, was developed and released from the Saskatoon Research Station in 1980. In B. juncea, genes for resistance to race 2 are present in most yellow-seeded Oriental mustards grown in Canada.

Three Alternaria species, A. brassicae (Berk.) Sacc., A. raphani Groves and Skolko and A. brassicola (Shew.) Wilts can cause yield losses in the oilseed brassicas. In general, A. brassicae is the most widespread and destructive form. While there are no known sources of resistance to Alternaria in B. campestris, several B. napus and B. juncea cultivars have shown a degree of resistance (Kolte, 1985). Subsequent investigations suggest that most, if not all, are susceptible under epidemic conditions. Thus, the identification of a good source of resistance within the brassicas continues to be an important breeding objective.

Many other diseases cause economic losses, including root rot (Rhizoctonia solani Kuhn., Fusarium spp.) club root (Plasmodiophora brassicae), light leaf spot (Pyrenopeziza brassicae), bacterial rot (Xanthomonas campestris), aster yellows and phyllody (mycoplasms), broomrape (Orobanche), and several viral diseases. Breeding for resistance to many of these pests is underway in those countries where weather conditions and cropping systems favor the development of these organisms. Kolte (1985) has recently reviewed the literature on these pathogens.

Early Maturity. In production areas such as western Canada, where the average number of frost-free days in the growing season is less than 100, early-maturing cultivars are essential. The B. campestris species, which requires only 85 to 90 days from seeding to maturity, is well suited to northern growing regions. However, growers would prefer to produce the higher-yielding cultivars of B. napus. 'Argentine,' the original B. napus introduction into Canada required 101 days to mature and was at high risk to frost injury. Breeding efforts in the last 40 years have resulted in the release of the cultivar 'Westar,' which requires only 95 days to mature while yielding significantly more seed and oil than previous cultivars. The current objective is to breed cultivars that mature in less than 95 days and yield more seed and oil than 'Westar.'

In central China, the development of early-maturing, high-yielding cultivars is a major breeding objective. The rapeseed crop must be
planted and harvested within very narrow time limits so that two crops of rice and one of rapeseed can be grown on the same land in 1 year.

*Herbicide Tolerance.* The introduction of the herbicide trifluralin for control of many broad-leaved weeds in *Brassica* oilseed crops was a major breakthrough in crop management. However, not all broad-leaved weeds are controlled by this herbicide and cruciferous weeds, such as wild mustard (*Sinapis arvensis*) and stinkweed (*Thlaspi arvense*), remain major problem weeds in some regions. Bird rape, a weedy form of *B. campestris*, was found growing in maize fields in Quebec, Canada, sprayed with atrazine herbicide. It was shown that these bird rape plants were tolerant to the triazine family of herbicides and that this herbicide tolerance, based on a mutated chloroplast protein, was cytoplasmically inherited (Souza-Machado et al., 1978; Golden and Haselkorn, 1985). This finding presented the first opportunity for chemical control of cruciferous weeds in rapeseed. Triazine tolerance has been transferred, by repeated backcrossing with the tolerant parent as the female, to the oilseed forms of *B. campestris* and *B. napus* (Beversdorf et al., 1980). Unfortunately, the mutated chloroplast protein is associated with reduced efficiency of electron transfer within the photosynthetic apparatus (Burke et al., 1982). As a result, seed yields of triazine-tolerant strains and cultivars are 20 to 30% lower and oil contents are significantly reduced compared with their recurrent parent. Thus, triazine-tolerant cultivars, such as 'OAC Triton' and 'Tribute,' are grown only in fields where a severe infestation of cruciferous weeds is expected or on atrazine-treated maize land. Selection or induction of herbicide tolerance associated with a more efficient electron transfer system is an important breeding objective.

Several biotechnology groups are engaged in transferring genes for tolerance to glyphosate, chlorsulfuron, and other herbicides into the oilseed brassicas. If such transfers can be accomplished without adversely affecting plant growth, the present triazine tolerance characteristic may become obsolete.

*Other Agronomic Objectives.* Other agronomic breeding objectives include greater resistance to lodging and shattering, ability to germinate and grow at low soil temperatures, and development of strains with decreased attractiveness to aphids.

**Quality Traits**

Breeding objectives for quality traits relate to the value of the oil and meal resulting from extraction and refining processes.
Oil and Protein Content. Oil is the most valuable component of the seed, having a monetary value 2 to 3 times that of the remaining high-protein meal. In most European countries, seed is purchased from the producer on an oil-percentage basis so that the oil yield per hectare establishes the grower’s monetary return. In most other growing regions, the grower is paid for the quantity of seed delivered. The value of the oil component and its relatively high heritability (Grami et al., 1977), plus the ease and speed with which oil content can be measured by wide line nuclear magnetic resonance (NMR) or near-infrared reflectance spectroscopy (NIR), has made increased oil content a prime breeding objective.

Correlations between the percentages of oil and protein are reported to be −0.81 for phenotypic and −0.71 for genotypic expressions (Grami et al., 1977). To maximize the value of the seed and maintain or expand the market for livestock and poultry feeding, it is necessary to select for high levels of both oil and protein. Grami et al. (1977) have shown that simultaneous selection for oil plus protein is effective. They reported a heritability of 0.33 for the sum of oil plus protein.

The development of yellow-seeded forms of the oilseed brassicas resulted in increased oil and protein content, as well as a desirable reduction in meal fiber levels. These favorable changes occurred because yellow seed coats are significantly thinner than brown seed coats, with the result that yellow seeds contain a greater proportion of the oil- and protein-rich embryo and less of the high-fiber hulls (Stringam et al., 1974; Jonsson and Bengtsson, 1970). The meal from yellow seed is more acceptable to the feed manufacturer because the completely yellow meal blends well with other feedstuffs allowing flexibility in formulations without altering the appearance of the finished feed. Pure yellow-seeded cultivars occur in the sarson subspecies of B. campestris and partially yellow-seeded cultivars of turnip rape, such as ‘Candle’ and ‘Tobin,’ have been developed. In B. juncea, the pure yellow-seeded cultivars ‘Lethbridge 22A,’ ‘Newton,’ ‘Domo,’ and ‘Cutlass’ have been developed for the condiment trade. Despite considerable research efforts, pure yellow-seeded strains of B. napus have not been stabilized in an agronomically acceptable background (Shirzadegan and Robbelen, 1985). Increased seed size reduces the percentage of hull and results in elevated oil and protein contents and reduced fiber levels (Hutcheson, 1984).

Oil Quality. The fatty acid composition of an oil determines its value for edible or industrial uses. Oils from Brassica seed crops have traditionally been characterized by high levels of the long-chain monoenoic fatty acids, eicosenoic and erucic. The other fatty acids contained in the oilseed brassicas are normally present in most other edible vegetable oils (Table 12-4).
Table 12-4  Typical Fatty Acid Compositions in Percent for High and Low Erucic (E) Acid Rapeseed Oils and Some Other Common Vegetable Oils

<table>
<thead>
<tr>
<th>Fatty Acid</th>
<th>Rapeseed</th>
<th>Other Major Oils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low E</td>
<td>High E</td>
</tr>
<tr>
<td>Palmitic</td>
<td>3.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Stearic</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Oleic</td>
<td>60.2</td>
<td>11.2</td>
</tr>
<tr>
<td>Linoleic</td>
<td>21.3</td>
<td>13.6</td>
</tr>
<tr>
<td>Linolenic</td>
<td>10.9</td>
<td>7.7</td>
</tr>
<tr>
<td>Eicosenoic</td>
<td>1.3</td>
<td>6.1</td>
</tr>
<tr>
<td>Erucic</td>
<td>0.5</td>
<td>55.1</td>
</tr>
<tr>
<td>Nervonic</td>
<td>tr</td>
<td>2.5</td>
</tr>
</tbody>
</table>

tr = trace amounts.

The development of gas-liquid chromatography (GLC) (Craig and Murtry, 1959), the application of paper chromatography (Thies, 1971), and fast and simple analysis techniques for the estimation of linoleic and linolenic acid levels in half seeds of rapeseed (Rakow and Thies, 1972) provided a rapid and accurate means of determining the fatty acid composition of minute quantities of oil. These developments provided a means for screening the large populations necessary to identify genetically modified plants with oil compositions that more closely meet the needs of existing markets and permit exploitation of new potential markets.

Fatty acid biosynthesis in *Brassica* oilseeds follows a pathway similar to that found in many other oilseed crops (Fig. 12-2). Each of the carbon chain elongation and desaturation steps is under enzymatic control and open to genetic manipulation (Stumpf and Pollard, 1983).

Breeding objectives for oil quality relate to the nutritional value and the storage or keeping characteristics of the oil, as well as to the enhancement and expansion of its industrial applications. Breeding for low erucic acid *Brassica* oil for human consumption was one of the first objectives. It was initiated in the mid-1950s when researchers first questioned the nutritional value of erucic acid. To meet this need, low erucic acid strains of *B. napus* (Stefansson et al., 1961), *B. campestris* (Downey, 1964) and *B. juncea* (Kirk and Oram, 1981) were bred. In low erucic acid genotypes, the carbon chain elongation system, which adds two carbon fragments to the carboxyl end of oleic and eicosenoic acids to form erucic, is genetically blocked. As a result, an entirely new high oleic acid vegetable oil
was obtained (Table 12-4). This new product has found wide acceptance, particularly as a liquid oil.

A high erucic acid oil is required by industry. Erucic acid is fractioned from the oil, converted to an amide, and sprayed on plastic products and extruding equipment as a slip agent. The applied erucamide ensures that the manufactured plastic products do not stick to each other or the manufacturing machinery. To service both the edible and industrial markets, cultivars with very low or very high erucic acid oils are required. A series of alleles that act in an additive manner to produce levels of erucic acid from less than 1% to more than 60% of the total fatty acids have been identified (Krzymanski and Downey, 1969). The fact that erucic acid is found only at the 1 and 3 positions of the glycerol molecule limits its content to a theoretical maximum of 66.6%. It may be possible to overcome this barrier because seed oils of nasturtium (Tropaeolum majus) and garlic wort (Alliaria officinalis) are known to contain over 70% erucic acid (Swern, 1964).

The second breeding objective for oil quality is to reduce the percentage of linolenic acid from 8 to 10% to less than 3% while increasing, or at least maintaining, the level of linoleic acid. Linoleic is a nutritionally important fatty acid which is the basis for the formation of prostaglandins and other essential body regulators. Linolenic acid, although polyunsaturated and an essential dietary fatty acid, is unwanted in an edible oil.
because its three double-bond structure is readily oxidized, resulting in off-flavors and reduced shelf-life of the oil.

Because linoleic and linolenic acids are produced by the same biosynthetic desaturation pathway (Fig. 12-2), selection for high linoleic acid has tended to increase the level of linolenic acid while selection for low linolenic acid tended to result in lower linoleic acid levels. Selection within the available germplasm may not achieve the breeding objective, although strains with less than 7% linolenic, combined with up to 30% linoleic, have been genetically stabilized at Saskatoon. The use of chemical mutagens resulted in the induction of two B. napus lines with linolenic acid contents of approximately 5 and 20% with unchanged and identical levels of about 20% linoleic acid (Rakow, 1973). More recently, Stefansson (1983), using these low linolenic mutants as a base, has developed agronomically acceptable summer B. napus lines with less than 3% linolenic acid, combined with a linoleic acid content of more than 22%. Swedish and Australian researchers were also successful in breeding for reduced levels of linolenic acid and increased levels of linoleic acid (Jonsson and Persson, 1983; Roy and Tarr, 1986). As a result, this oil quality objective is likely to be achieved and indeed surpassed in future Canadian B. napus cultivars, but will still have to be transferred into other oilseed Brassica species and forms in order to have a major impact on the world edible-oil market.

A third oil-quality objective is to increase the content of fatty acids with shorter chain lengths, such as palmitic and palmitoleic. Such a modification is of interest because there is a tendency for margarines made from 100% low erucic oils to form large internal crystals on storage. This tendency is associated with oils having a very high proportion (92 to 95%) of fatty acids with the same 18-carbon chain length. Although the problem can be overcome by blending another oil, such as palm, which is rich in palmitic acid or by adding a crystal retardant, the ultimate solution may be to increase the level of palmitic plus palmitoleic acids to 10 to 12% in Brassica oils. Swedish researchers have selected such material in B. campestris, (Persson, 1985), but how useful or acceptable an oil with such a fatty acid composition will be has yet to be determined.

Meal Quality

Amino Acids. The quantity of protein present in the meal and its amino acid balance is important to its marketability for livestock and poultry feeding. Brassica seed oils are relatively high in lysine, an essential amino acid deficient in cereal grains (Table 12-5). The high sulfur amino acid content of the meal is also beneficial when fed with grains, such as maize, in which these essential amino acids are limiting. In general, Brassica seed protein is considered equivalent in quality to that of soybean protein,
Table 12-5  Contents of Essential Amino Acids in Proteins from Oilseed Crops

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>Grams Amino Acid per 100 Grams Protein</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rapeseed</td>
</tr>
<tr>
<td>Arginine</td>
<td>5.8</td>
</tr>
<tr>
<td>Histidine</td>
<td>2.7</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>3.8</td>
</tr>
<tr>
<td>Leucine</td>
<td>6.8</td>
</tr>
<tr>
<td>Lysine</td>
<td>6.2</td>
</tr>
<tr>
<td>Methionine</td>
<td>1.9</td>
</tr>
<tr>
<td>Methionine plus cystine</td>
<td>4.0</td>
</tr>
<tr>
<td>Tryptophan</td>
<td>1.1</td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>3.8</td>
</tr>
<tr>
<td>Valine</td>
<td>4.9</td>
</tr>
<tr>
<td>Threonine</td>
<td>4.4</td>
</tr>
</tbody>
</table>

but an increase in the level of lysine and methionine could be an advantage in the market. Most breeding programs have assigned a relatively low priority to this breeding objective due to the time and expense associated with amino acid analysis.

Glucosinolates. Until recently, the feeding value of rapeseed meal has been limited due to the presence of sulfur compounds called glucosinolates. The vegetative tissue and seeds of cruciferous plants contain one or more of over 90 known glucosinolates (Fenwick et al., 1983). When cells of a crucifer are broken, in the presence of moisture, the myrosinase enzyme present in the plant tissues hydrolyzes the glucosinolates to form thiocyanates, isothiocyanates, or nitriles (Fig. 12-3). Although these glucosinolate breakdown products give the characteristic flavor and odor to Brassica vegetables and condiments, they are undesirable in animal feeds. In high concentrations, these compounds can reduce palatability and, in nonruminant animals such as swine and poultry, adversely affect iodine uptake by the thyroid gland. Thus they reduce feed efficiencies and weight gains (Bell, 1977; Fenwick et al., 1983).

To avoid nutritional problems in high glucosinolate rapeseed, the myrosinase enzyme is heat inactivated as one of the first steps in the oil-extraction process. Because the intact glucosinolates are relatively innocuous, such processed meal can be freely fed to ruminants and, at controlled levels, to swine and poultry. The ultimate breeding goal is to produce cultivars that contain minimal amounts of glucosinolates in their seed and meal.

The development of rapid and accurate methods for the determination
of glucosinolate levels in seed in the early 1960s led to the screening of available germplasm at the Saskatoon Research Station, and eventually to the identification of the *B. napus* cultivar ‘Bronowski’ from Poland, as having a low glucosinolate content (Finlayson et al., 1973). This cultivar was utilized in breeding programs to combine the two quality characteristics of low glucosinolate and low erucic acid. The first double-low spring *B. napus* cultivar ‘Tower’ was released for Canadian commercial production in 1974.

The development of low glucosinolate *B. campestris* was more difficult because genes for the low glucosinolate characteristic were not found within the existing germplasm. The partially yellow-seeded, low erucic, low glucosinolate *B. campestris* cultivar ‘Candle,’ released in 1977, was developed at Saskatoon through interspecific crosses between the low erucic acid *B. campestris* cultivar ‘Span,’ the low glucosinolate *B. napus* cultivar ‘Bronowski,’ and the yellow-seeded *B. juncea* cultivar ‘Lethbridge 22A,’ followed by selection and backcrossing to the *B. campestris* parent. Genes for the low glucosinolate characteristic have not been found in the *B. juncea* species, although it remains a prime breeding objective.

In *B. napus* cultivars, the glucosinolate content per gram of moisture-free, oil-free meal has been reduced from 150 μmoles to less than 15 μmoles, while in *B. campestris* cultivars the reduction has been from 90 μmoles to less than 30 μmoles. Many feeding trials with low glucosinolate meal have established its superior nutritional quality, resulting in the removal of the need for special feeding limits for nonruminant animals. The improved nutritional qualities of low erucic acid, low glucosinolate cultivars were so well accepted by Canada’s domestic and foreign markets that these characteristics are now prerequisites for new cultivars. The term canola was coined to identify *B. napus* and *B. campestris* seed producing oil with less than 2% erucic acid (canola oil) and with less than

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**Figure 12-3** General structure of glucosinolates and enzymatic hydrolysis products.

![Diagram of glucosinolates and enzymatic hydrolysis products](image-url)
30 µmoles equivalent of 3-butenyl isothiocyanate per gram of moisture-free, oil-free meal (canola meal). These limits are for the commercial crop; therefore, breeding lines and pedigreed seed of canola cultivars should be well below the allowed maximum levels. Erucic acid contents of <0.5% in the oil and glucosinolate content of <10 µmoles/g of meal is a breeding target.

In Canada, Sweden, and Denmark, spring *B. napus* cultivars of canola quality have been bred that are agronomically superior to the traditional rapeseed cultivars. As of 1986, the European winter crop is of low-erucic, but high-glucosinolate quality. A total conversion to canola quality in Europe is expected as soon as high-yielding, winter-hardy forms are developed. In China, India, Pakistan, and other major producing nations, breeding for canola quality has a high priority.

Sinapine. *Brassica* oilseeds contain approximately 1 to 1.5% sinapine, an ester of sinapic acid and choline (Josefsson and Uppstrom, 1976). It has been suggested that the bitter taste of sinapine could affect the palatability of the meal; however, the main objection to sinapine is that it can cause an objectionable fishy odor in brown-shelled eggs produced by certain strains of hens (Pearson et al., 1980). The reduction or elimination of sinapine could have an important market impact in regions such as the United Kingdom where brown-shelled eggs have a significant market share. The lack of a fast and accurate analytic method for sinapine has hindered progress toward this breeding objective.

Phytic Acid. *Brassica* oilseeds contain about 1.5% phytic acid which is similar to levels found in other oilseeds. Because it is a strong chelating agent, the bioavailability of some minerals, particularly zinc, is reduced and zinc deficiencies have been noted in some feeding trials (Erdman, 1979). Breeders have not given the reduction of phytic acid a high priority because of the lack of suitable methods for estimating phytic acid content (Uppstrom and Svensson, 1980) and because zinc supplementation in the diet will readily and cheaply overcome the potential problem (Shah et al., 1979).

**STEPS IN CULTIVAR DEVELOPMENT**

In the breeding of improved *Brassica* oilseed cultivars, there are many decisions breeders must make. The first decision is the number of species and crop forms to improve. A breeder must decide whether to concentrate only on edible oil cultivars or try to service the smaller but important industrial market as well. Although the environment under which the
breeding studies are conducted may limit the options, it is almost certain a choice will have to be made as to the allocation of resources among species, forms, and markets.

Once the broad outline of the program has been established, the breeder must decide on the essential characteristics to be incorporated into the improved cultivar, if it is to be successful in both the field and the market place. There must be an awareness of problems that growers want solved, such as disease resistance and lodging, as well as the desires of the processor and end user.

Once the essential and desirable breeding goals have been identified, an assessment of the chances for success and the probable time required should be made. It may become apparent in formulating the development program that certain characteristics can be incorporated more rapidly than others, so that a planned series of cultivar releases may be possible. This type of analysis has been very useful in the rapidly changing and evolving rapeseed crop where all segments of the industry need to be informed years in advance as to the type of changes they may expect in such traits as quality of oil and meal, significant yield advances from hybrid cultivars, quality improvements through changes in seed color, and changes in oil content. Without providing advanced information to the industry, serious damage to markets can occur, rather than the rapid acceptance the breeder expected for the new improved cultivar.

After the desired parameters of the new cultivar have been established, careful consideration must be given to the selection of parents that can and should be used to develop the new cultivar through crossing and selection, given their individual and complementary characteristics. Decisions must be made on the breeding strategies to be applied in the management of segregating breeding populations. The number of plants and progenies that can be accommodated in the field, growth facilities, and laboratory will be determined by the resources available. The selection intensity for each characteristic under improvement and the sequence in which the selections are carried out can have a major impact on the rapidity with which the desired genetic advance is achieved.

The breeding system used will vary with the species and form being bred, as well as the mode of inheritance and the importance of each of the characteristics under selection. For example, the breeder may wish to develop a high-oil, low erucic acid cultivar of *B. juncea*, using as parents the Australian lines with low erucic acid and low oil content (Kirk and Hurlstone, 1983) and the Russian cultivar ‘Donskaja,’ which has high oil and high erucic acid. Because the inheritance of erucic acid content is relatively simple and that of oil content is quantitative, a backcross-breeding approach to the high-oil parent is the obvious choice. However, a decision must be made as to the sequence in which selections for oil quantity and
quality are made. The first option is to analyze for erucic acid in the BC₁,F₁ and BC₂,F₂ generations using the half-seed technique to ensure the progeny to be evaluated for oil and agronomic characteristics are all low erucic acid genotypes. The second option is to sow a much larger population of progeny rows from BC₂,F₂ plants in the field and delay selection for erucic acid until after the oil and agronomic evaluations have been made. Option one would require a high capacity for erucic acid analysis and a large greenhouse facility. On the other hand, if ample field nursery resources are available to handle large numbers of progeny rows, the second option may offer the greater probability of finding the best combination. Other examples will be discussed in the section on breeding procedures.

The timing of crosses and the dates when the progeny will be planted and harvested in greenhouses or growth chambers must be carefully scheduled. The goal is to obtain the greatest genetic advance possible each year and have seed of the desired generation available for field evaluation at the normal sowing date for that species or crop form.

In the largely self-pollinating B. napus and B. juncea species, backcrossing and pedigree breeding systems have been used successfully. Normally, breeding material of B. napus and B. juncea is evaluated as the progeny of F₂ and F₃ plants in single rows, followed by replicated, multiple-row yield trials. In the self-incompatible B. campestris species, backcrossing and recurrent selection have been employed most frequently.

Following extensive evaluations for all relevant agronomic and quality characteristics, the best lines are evaluated in official cooperative trials over a broad range of environments (years and locations). To receive registration and licensing, a line must exceed the performance of the best current cultivar in at least one or more important economic characteristics. It generally takes 8 to 10 years from the time the cross is made until a cultivar is registered.

**SOURCES OF GENETIC VARIABILITY**

**Types of Parents and Populations**

The amount of genetic variation available to the Brassica oilseed breeder is very great. A broad gene pool is available within and among the Brassica species. The rapeseed and mustard species B. napus, B campestris, and B. juncea are closely related to one another and to B. nigra, B. oleracea, and B. carinata (U, 1935) (Fig. 12-4). Cytological evidence indicates that these species originated from an extinct common ancestor with a basic chromosome number x = 5 or 6 (Heyn, 1977).
It is believed that the \( b \) genome of \( B. \) nigra \((n = 8)\) includes a double tetrasomic, the \( c \) genome of \( B. \) oleracea \((n = 9)\) has a triple tetrasomic, and the \( a \) genome of \( B. \) campestris \((n = 10)\) is double tetrasomic for two chromosomes and hexasomic for another. If the six basic chromosomes are identified by the letters \( A, B, C, D, E \) and \( F \), the formula for the three genomes are \( a = AABCDDEEFF; b = ABCDDEFF \) and \( c = ABBCCDEEF \) (Robbelen, 1960).

Natural crosses between diploid species, followed by chromosome doubling to form the amphidiploid, probably occurred at several times in nature where the species grew in close proximity. It is interesting to note that the \( a \) genome of \( B. \) campestris is common to the three economically important \( Brassica \) oilseed species. It should be noted that all three diploid species are self-incompatible, while the derived amphidiploids are self-fertile.

Studies on the crossability of rapeseed and mustard, within and among species of the \( Brassica \) genus and allied genera, are important for the breeder because of the excellent possibilities to transfer economi-
cally important traits from related genera and species to the commercial crop. *Brassica* species and related genera can be classified into cytodesmes based on the crossability of related subspecies with the same chromosome number. Harberd (1976) defines cytodesmes as follows:

If two populations have a common chromosome number and are easily crossed to form a hybrid, which is neither obviously weak in vigor nor of low fertility, then they belong to the same *cytode.me*. By contrast different cytodesmes (which sometimes have the same chromosome number) are (a) difficult to cross, or (b) give a weak hybrid, or (c) have a sterile hybrid, and frequently exhibit all three criteria.

This is a very useful definition of a *Brassica* species for practical plant breeding applications. The success rate of interspecific hybridization depends on the genetic relationship of the parents and the direction of the cross. In general, the interspecific cross is more successful if an allopolyploid species, such as *B. napus* or *B. juncea*, is used as the female parent, particularly if the allopolyploid has one genome in common with the pollen parent. Hybrids between monogenomic species are more difficult to obtain, with success rates of between 0.002 and 0.03 hybrids per pollinated flower (Downey et al., 1980). Studies on the relationship of *Brassica* genomes and allied genera (Harberd, 1972; Mizushima, 1980) indicate that partial homology exists among genomes of the *Brassica*, *Sinapis*, *Diplotaxis*, *Eruca*, and *Raphanus* species of the Cruciferae.

The use of embryo rescue and protoplast fusion techniques present the possibility of combining characteristics from different genera. These techniques may, in time, parallel the successes achieved in transferring characteristics among *Brassica* species. Examples of successful gene exchanges between *Brassica* species include the low glucosinolate trait from *B. napus* into *B. campestris* cv. 'Candle,' the genes for blackleg resistance from *B. juncea* into *B. napus* (Roy, 1984), and white rust resistance genes from *B. napus* to *B. campestris* (Rimmer and Stefansson, 1986).

Although interspecific and intergeneric crosses have much potential, the genetic variability of the *Brassica* landraces has not yet been fully exploited and, with few exceptions, the characteristic desired by the breeder can be found within the species of interest or a close relative. Examples include resistance to blackleg in the *B. napus* and *B. campestris* species found in epidemic areas in France and Australia, the selection of very early-maturing *B. napus* plants in Canada, wide variation found in oil composition, and very high oil content lines found in Russian *B. juncea* selections.
Population Development by Hybridization

*Procedures for Artificial Hybridization.* In all three species, controlled crossing is done by emasculating flower buds that are due to open on the same or the following day (Fig. 12-1). The stigma is dusted with freshly dehisced pollen from individual stamens. If required, pollen viability can be maintained in storage for up to 5 weeks (Chiang, 1974).

Intraspecific *Brassica* crosses are easily performed. Just prior to anthesis, buds are emasculated by removing the six undehisced anthers (Fig. 12-1). Petals and sepals may be removed or retained according to the preference of the breeder. The stigma is receptive up to 3 days prior to flower opening. A flower with pollen-laden anthers from the male parent is applied to the stigma of the emasculated flower. Pollen also may be collected from the male parent on a small camel-hair brush and dusted onto the stigma of the female parent. Immediately following pollination, the flower must be covered to exclude unwanted pollen. A complete raceme can be protected with a glassine bag, or if a number of different crosses are to be made on the same raceme, small plastic bags may be used to cover individual stigmas (Kondra and Downey, 1968). Fertilization normally occurs within 24 hours of pollination; however, protective bags should remain in place for at least 3 days. The success rate for intraspecific crosses is usually greater than 90% and a single pollinated flower will normally produce 20 or more seeds.

*Procedures for Natural Hybridization.* Both wind and insects can disseminate *Brassica* pollen over long distances. Therefore, isolation distances of at least 366 m are desirable to maintain the purity of breeding stocks (Stringam and Downey, 1978). Glassine bags normally are used because *Brassica* pollen is small and cloth or mesh cages are not completely effective in excluding foreign pollen. The self-incompatibility characteristic of *B. campestris* precludes the use of selfing bags and increases the probability of contamination by foreign pollen. Thus, good spatial isolation of seed-increase blocks is required to maintain the purity of breeding populations and cultivars of this species. However, the incompatibility system does provide the basis for a random sampling of gametes in recurrent selection crossing blocks.

Honeybees, bumblebees and leafcutter bees may be used to transfer pollen in the field or greenhouse. However, it is difficult to establish the optimum temperature conditions for both plant growth and maximum bee activity in a growth chamber or greenhouse. Under field conditions, high bee populations can be very effective pollinators. Honeybees and leafcutter bees will likely be utilized in hybrid seed-production fields to ensure a
high level of hybrid seed and a low incidence of stray pollen contamination.

**Mutagenesis**

A small number of mutation studies using ionizing radiation (X-rays and cobalt-60) and chemicals, such as ethylmethane sulfonate (EMS), have been carried out in *Brassica* oilseed crops. Because of great variability within the genus for most of the economically important characteristics, it is normally not necessary to resort to the use of mutagens. The exception has been the reduction of linolenic acid in the seed oil. Selection in untreated populations have not yielded genotypes with significantly lower linolenic acid levels from the normal 8 to 12%. However, using EMS and X-rays on *B. napus* seed, mutant lines with 3% linolenic acid were identified (Rakow, 1973; Robbeln and Nitsch, 1975).

**BREEDING PROCEDURES**

Rapeseed breeding techniques vary greatly and have evolved from simple mass selection to hybrid cultivar development. Scientific and practical considerations, as well as breeding objectives, have an influence on the breeding procedures used.

The two amphidiploid species, *B. napus* and *B. juncea*, are largely (70%) self-pollinating. In the following discussion, the examples given for *B. napus* can also be applied to *B. juncea* improvement. Except for the self-fertile Indian sarson types, all other *B. campestris* types are self-incompatible and cross-fertile. With the exception of backcrossing, breeding procedures suitable for *B. napus* and *B. juncea* are normally not appropriate for *B. campestris*.

**Backcrossing**

The backcrossing approach has been successfully used to transfer simply inherited traits, such as low erucic acid and glucosinolate content into adapted lines and breeding populations of *B. napus* and *B. campestris*.

The erucic acid content of a seed is controlled by the genotype of the embryo, not by the genotype of the mother plant. This means that individual F2 seeds borne on F1 plants have different erucic acid levels. The half-seed method makes it possible to select individual seeds on the basis of their erucic acid content (Downey and Harvey, 1963). Selected seeds are
grown into plants and backcrosses are performed. The backcross procedure used for the transfer of the zero erucic acid alleles is outlined in Fig. 12-5. In *B. napus* (Harvey and Downey, 1964) and *B. juncea* (Kirk and Hurlstone, 1983), two loci, each with two alleles determine the erucic acid level expressed. In *B. campestris* (Dorrell and Downey, 1964), two alleles at a single locus control erucic acid synthesis. The heterozygous F₁ plant (*E₁e₁E₂e₂*) is backcrossed to the recurrent high erucic acid parent (*P₁*), heterozygous BC₁F₂ seeds (*E₁e₁E₂e₂*) are selected, and plants obtained from the seeds are backcrossed. This permits a backcross to be made every generation, thus speeding up the breeding program. After the last backcross, a selfing generation is required to identify the zero erucic acid (*e₁e₁e₂e₂*) genotype. This procedure was also very effective in transferring the zero erucic acid characteristic from spring types of *B. napus* into adapted high-yielding winter forms of this species. A similar approach is being used in *B. campestris* to transfer the high erucic acid characteristic from yellow sarson into ‘Tobin,’ a high-yielding, white rust resistant cultivar of *B. campestris*. After backcrossing to the zero erucic acid cultivar ‘Tobin,’ selection for heterozygous (*E₁e₁*) genotypes is carried out using the half-seed method, and the selected plants are further backcrossed. At the end of the backcross procedure, high erucic acid (*E₁E₁*) genotypes can be isolated.

The backcross approach also was used in the transfer of the low glucosinolate characteristic from the *B. napus* cultivar ‘Bronowski’ into adapted cultivars and strains of this species. The glucosinolate content of seeds of *B. napus* is under maternal control. The low-glucosinolate characteristic is recessive to high-glucosinolate levels and controlled by several loci (Kondra and Stefansson, 1970; Lein, 1972). This inheritance pattern makes the backcrossing procedure more difficult. A backcross to the high-glucosinolate recurrent parent can still be made in every generation, if test crosses are made to a low glucosinolate line for the identification of heterozygous individuals. The heterozygous plants are used as parents in the following backcross generation (Morice, 1974).

**Pedigree Selection**

For the predominantly self-pollinating *B. napus* and *B. juncea* species, the most commonly used breeding procedure in cultivar development is pedigree selection. The breeding objective must be clearly defined and suitable parents identified. Potential parents should be intensively evaluated over a wide range of environments so that their attributes and faults are clearly known before crosses are made and the selection program begins.
Initial Cross

\[ \text{P}_1 \quad (1\%) \text{ e,e,e,e,e} \quad \times \quad \text{P}_2 \quad (40\%) \text{ E,E,E,E} \]

BC$_1$F$_1$

\[ \text{BC}_1\text{F}_1 \quad (20\%) \text{ E,e,E,e} \quad \times \quad \text{P}_1 \]

Analyze half of each seed for erucic acid. Plant half seeds with E,e,E,e genotype.

BC$_1$F$_2$

\[ \text{BC}_1\text{F}_2 \quad (40\%) \text{ E,E,E,E} \quad (30\%) \text{ E,E,E,e} \quad (30\%) \text{ E,e,E,E} \quad (20\%) \text{ E,e,E,e} \quad \times \quad \text{P}_1 \]

Discard seeds

Analyze individual half seeds for erucic acid.

BC$_1$F$_2$

\[ \text{BC}_1\text{F}_2 \quad \text{E,E,E,E} \quad \text{E,E,E,e} \quad \text{E,e,E,E} \quad \text{E,e,E,e} \quad \times \quad \text{P}_1 \]

Discard seeds

Analyze individual half seeds for erucic acid.

BC$_1$F$_2$

\[ \text{BC}_1\text{F}_2 \quad \text{E,E,E,E} \quad \text{E,E,E,e} \quad \text{E,e,E,E} \quad \text{E,e,E,e} \quad \text{Self plants} \]

Analyze individual BC$_1$F$_2$ half seeds and plant those with e,e,e,e genotype.

Figure 12-5  Backcross breeding scheme to transfer the low erucic acid characteristic from a low erucic acid genotype (P$_1$) to an adapted high erucic acid cultivar (P$_2$), as used in the breeding of the first low erucic acid B. napus cultivar ‘Oro.’ Each E allele contributes about 10% and each e allele <0.25% erucic acid.
Once the parents have been selected, artificial hybridization is performed, usually in the greenhouse. Five to 10 F₁ plants from each cross are grown in the greenhouse and the plants within each cross are inter-pollinated or selfed. F₂ seeds from F₁ plants of each cross are harvested in bulk and sown in a field nursery. Depending on the objective of the cross, 1000 to 3000 open-pollinated F₂ plants are individually harvested. The following year, F₃ progeny of each plant are grown in a single-row nursery for agronomic evaluation. Depending on the amount of resources and available seed, as well as the reliability with which various agronomic and quality characteristics can be assessed, the single-row nursery may have one, two or three replicates. The rows are evaluated visually. Five to ten single F₃ plants may be harvested from each selected row. In the F₄ generation, selection is practiced first among families of progeny rows (F₃-derived lines) that were obtained from plants harvested from the same F₃ progeny row, and then among rows within selected families.

At this stage of the program, the breeder has the option of continuing the selection process by harvesting individual plants from selected rows for further progeny testing and selection or to undertake yield trials of the selected F₅-derived lines harvested in bulk. The option chosen depends on the breeder’s assessment of whether visual pedigree selection in the F₅ will result in significant genetic advance or only small improvements which may not be worth the effort. Experience indicates that the amount of variation within F₄ families is a good indication whether further selection may be effective. In some programs, continued pedigree selection up to the F₆ generation has resulted in measurable agronomic improvements.

An actual pedigree scheme, used in the breeding of a European winter B. napus cultivar is illustrated in Fig. 12-6. The breeding goal was to produce a cultivar with high yield, winter hardiness, and low erucic acid using as parents the low-erucic acid, spring-rape cultivar ‘Oro’ and the winter-hardy, high-yielding cultivar ‘Rapol.’ Pedigree selection was initiated within the BC₂ population of the cross ‘Oro’ × ‘Rapol.’ About 10 BC₃F₁ plants were grown and selfed in the greenhouse. About 32,000 BC₃F₃ seeds were analyzed for erucic acid content by the half-seed method, the 2000 seeds which contained less than 2% erucic acid were selected, the plants obtained from them were grown in a field nursery, and the plants were selfed. A single progeny row was sown from selfed seed of each BC₃F₃ plant in the field with check cultivars sown every tenth row. Open-pollinated BC₃F₃ plants were harvested from selected rows which had the greatest winter hardiness and good agronomic performance. Seeds from selected BC₃F₃ plants were sown in progeny rows, grouped by families, with check cultivars separating each family. Visually superior BC₃F₃-derived lines were identified and harvested in bulk. The following
Figure 12-6 Pedigree breeding scheme, with selfing in the BC$_2$F$_2$ generation, to develop a low erucic acid, high-yielding, winter-hardy B. napus cultivar from a cross between the high erucic acid winter B. napus cultivar 'Rapol' and the low erucic acid spring B. napus cultivar 'Oro.'
season, the BC$_3$F$_3$-derived lines were evaluated for yield in a multiple-row plot with three replications at one location. The best performers from this test were advanced to multilocation tests, with the superior lines entering official trials the following year. Individual open-pollinated plants also were harvested within the selected BC$_3$F$_3$-derived lines, and a further selection cycle was conducted by sowing their progenies in a single-row nursery.

Backcrossing and Pedigree Selection

A combination of backcrossing and pedigree selection in segregating generations is being used for the incorporation of blackleg resistance into adapted Canadian *B. napus* cultivars. Blackleg-resistant Australian and European lines were crossed with the cultivar ‘Regent.’ The F$_1$ was backcrossed to ‘Regent’ and blackleg resistant plants selected in the BC$_1$F$_2$ generation. This was followed by pedigree selection for blackleg resistance and agronomic performance for three generations. Lines obtained combined blackleg resistance with acceptable maturity, but oil contents and seed yields were below expectations. The improved lines were used in a second program of crossing and backcrossing to ‘Westar,’ a cultivar with high seed yield and high oil content.

Selection for blackleg resistance, seed yield, and oil content will be performed in generations after the backcross. Only one backcross is carried out before reselection is initiated because no information is available on the inheritance of the blackleg resistance trait, and recovery of the resistance after backcrossing is essential.

The breeding of the spring *B. napus* cultivar ‘Westar’ is a further example of the combination of backcrossing and pedigree selection (Fig. 12-7). The initial low erucic acid plants were isolated from the German cultivar ‘Liho,’ a spring-rape type (Stefansson et al., 1961). These selections were crossed to high erucic acid Canadian cultivars. ‘Golden’ was crossed to the ‘Liho’ selection to produce the cultivar ‘Oro,’ which then was crossed with ‘Target’ to produce ‘Zephyr.’ All cultivars at that time had high glucosinolate levels. Low glucosinolate selections were later identified in the cultivar ‘Bronowski,’ a poorly adapted spring rape from Poland. Low glucosinolate selections were crossed with line S61-105, an early-maturing selection from the cultivar ‘Target.’ F$_2$ plants from this cross were selfed, low glucosinolate segregants identified, and their F$_3$ progeny crossed to the low erucic acid cultivar ‘Zephyr.’ Progeny evaluation identified F$_2$-derived lines from the ‘Zephyr’ cross that had the required quality and agronomic traits. F$_4$ plants from selected lines were
outcrossed to an agronomically superior line, S68-2895, having a low glucosinolate but high erucic content.

$F_2$ segregants low in erucic acid and glucosinolate were crossed with 'Midas,' a cultivar with high yield and zero erucic acid. To ensure the recovery of canola quality, $F_2$ plants were crossed with the cultivar 'Tower,' which has low erucic acid and glucosinolate content. Selections for quality and agronomic characters were conducted over four generations. $F_4$-derived lines with desired quality characteristics were identified and ad-
vanced into replicated yield tests. In 1982, the F₃-derived line ZN6-2836 was licensed as the cultivar ‘Westar.’ By 1985, ‘Westar’ occupied more than 90% of the total western Canadian *B. napus* hectarage (Prairie Pools, 1985).

**Early-Generation Testing**

The evaluation of progeny from even a small number of crosses requires a considerable amount of field and laboratory resources. The identification of crosses that are likely to provide superior genotypes is an important consideration. Yield testing of bulk populations in the F₂ and F₃ generations as a means of identifying superior crosses has not been used by rapeseed breeders, but the potential of this breeding tool is under investigation.

**Recurrent Selection**

The standard procedure for improving populations of the cross-pollinated *B. campestris* species is recurrent selection (Fig. 12-8). Populations for improvement can be landraces, progenies from crosses, or any other segregating population. Recurrent selection typically starts with the harvesting of individual open-pollinated plants from the source population. A portion of the seed from each plant is sown in a single progeny row and the remaining portion of the seed of these plants is placed in reserve. The agronomic characters of the progeny rows are evaluated visually, and superior rows are identified. The selected rows are harvested separately and their seeds are analyzed for one or more characters, including oil percentage, glucosinolates, seed color, protein, seed size, and fiber. Equal quantities of reserve seed from selected single plants, based on their progeny performance, is composited. The first cycle of recurrent selection is complete when the new composite is grown in an isolated plot where random matings occur among the plants within the composite. The second cycle of recurrent selection starts with harvesting of single plants from this composite. A bulk seed sample is harvested from the remaining plants of each composite for use in replicated yield trials to determine response to selection in each recurrent selection cycle for the characteristics under improvement. In Canada, recurrent selection in the summer annual *B. campestris* species is most efficient when the composite crossing block is grown in the southern United States during the winter months, from which plants are harvested for progeny testing the next summer in Canada. This procedure allows the completion of a full cycle of recurrent selection each year.
Figure 12-8  Recurrent selection breeding scheme for \textit{B. campestris}, as currently practiced at the Saskatoon Research Station. The initial composite could be an \textit{F}_2 or any segregating population.

Recurrent selection is continued as long as a reasonable response to selection is anticipated. Each cycle of recurrent selection produces a new population that may be a potential cultivar. The expensive and time-consuming work of yield testing many strains in replicated tests, as is required with the pedigree method, is reduced. Thus, most of the resources available for breeding can be directed toward selection. Although \textit{B. campestris} cultivars developed by recurrent selection or other breeding methods are relatively uniform for essential agronomic and qual-
ity traits, such cultivars must contain a high level of heterozygosity and heterogeneity to express the required plant vigor and seed yield.

Breeding objectives for new cultivars are numerous, and overall selection intensity increases geometrically with each trait under selection. This makes it very difficult to improve a population for several characteristics simultaneously. Therefore, specialized composites are formed, each for the improvement of one or only a few characteristics. After sufficient progress has been achieved within each specific composite, the breeder combines two or more composites to form a population to more easily develop a new superior cultivar.

Utilization of Heterosis

*Hybrid Cultivars.* F₁ seed produced by artificial hybridization has shown high levels of heterosis for seed yield in both spring and winter forms of *B. napus* (Sernyk and Stefansson, 1983; Grant and Beversdorf, 1985; Lefort-Buson and Dattee, 1982). Up to 40% heterosis for yield was reported for summer rape and 60 to 70% for the winter form, with the average heterosis being 10 to 20%. This level of heterosis is sufficient to justify the efforts currently underway to develop cytoplasmic male-sterile (cms), genetic-restorer systems for production of hybrid cultivars. Several cytoplasms are available for inducing male sterility.

*Raphanus*-Based cms. Ogura (1968) found male sterility in a Japanese radish cultivar. All Japanese radish cultivars were effective maintainers, and European cultivars restored fertility. This source of male sterility was used by Banneroat et al. (1974) in crosses with *B. oleracea* to produce a cms *B. oleracea* for which no restorer lines could be found. In a further cross of the cms *B. oleracea* to *B. napus*, Banneroat et al. (1977) introduced the nuclear genes of *B. napus* into the *Raphanus* cytoplasm to develop a cms *B. napus*. The sterility of the cms *B. napus* is stable under a wide range of environments, and female fertility of the cms plants seems to be adequate, but restorer genes have not yet been identified. It was observed that leaves of young cms plants were chlorophyll deficient, especially at lower temperatures. Because of these difficulties, only limited attempts are being made to further develop the *Raphanus* cms system.

Bronowski-Shiga-Thompson cms. This cytoplasmic male sterility was first described by Thompson (1972). He identified cms plants in the F₄ generation of crosses between summer and winter type *B. napus* cultivars in which the summer *B. napus* cultivar 'Bronowski' was used as the male parent. This type of male sterility is very unstable, with the sterility break-
ing down at high temperatures. Because most *B. napus* cultivars carry restorer genes for this type of cms, it is a difficult system to work with.

Polima cms. The Polima cms is the most promising cms system in *B. napus*. It is reported to have stable male sterility under various environments. Restorer genes are available and restoration of male fertility in the hybrid seems to be satisfactory. Reports indicate that restoration of pollen fertility is controlled by one major gene (Buzza, 1984). The first commercial *B. napus* hybrids, based on the Polima cms system, appeared in Canadian official trials in 1986.

Korean cms. A cms system in *B. napus* has been described by Lee et al. (1976). The existence of restorer genes has been reported, but the system has not been investigated as extensively as other *B. napus* cms systems.

Cytoplasmic male sterility also was discovered in *B. juncea* (Rawat and Anand, 1979). The sterility is stable under various environments. Fertility restorer genes for this cms system have been identified in other *Brassica* species, with those from *B. campestris* and *B. nigra* being the most effective. By crossing these two species, it is hoped that fertility restoration can be increased (Anand et al. 1985).

*B. campestris* hybrids have shown high levels of heterosis for seed yield. Hybrids have yielded about 40% more than the cultivar ‘Candle’ (Hutcheson et al. 1981). This level of heterosis is substantial and warrants further investigation. In F₁ hybrids between European and Canadian spring *B. campestris* cultivars, average heterosis for seed yield is only 5 to 10% (Falk, 1985).

The utilization of heterosis in hybrid cultivars of *B. campestris* would require a workable cms system. Such a system has been developed by crossing and backcrossing the vegetative-type *B. campestris* cultivar ‘Yukina’ into *Diplotaxis muralis* (Hinata and Konno, 1979). The resulting cms *B. campestris* cultivar had stable male sterility. Restorers have been identified for this system. However, the genes for maintenance of cms will have to be transferred into adapted oilseed forms of *B. campestris* before hybrids will be economically feasible.

It is possible to produce hybrid cultivars with male sterility controlled by nuclear genes if adequate and inexpensive labor is available. In China, hybrid seed has been produced with genetic male sterility in *B. napus* by removing male-fertile segregants from the female parent before flowering (Lee and Zhang, 1983). Because of the high labor requirement for roguing, such a system is not feasible in western countries.

*Synthetic Cultivars.* In *B. napus* and *B. juncea*, a portion of the heterosis found in hybrid cultivars could be obtained with synthetic cultivars by
making use of the 20 to 30% outcrossing that occurs in these species. In a
two-line synthetic, with 30% outcrossing, only 15% of the plants in the
Syn 1 generation are hybrids and contribute to heterosis. In winter *B.
apus*, some heterosis has been demonstrated in experimental synthetic
cultivars (Schuster, 1982). It may be that the proportion of hybrids in the
synthetic could be increased by increasing the number of lines in the syn-
thetic and by selection of lines showing a higher degree of outcrossing.
Similar attempts to utilize heterosis in spring *B. napus* synthetics in
Canada were unsuccessful.

Self-incompatibility. *B. campestris* is characterized by a sporophytically
determined self-incompatibility system which leads to almost complete
outcrossing. Self-incompatibility can be overcome by bud pollination and
inbreds can be obtained. These inbreds show high levels of inbreeding
depression and are very difficult to maintain through continued selfing.

Self-incompatible plants have been found in *B. napus*. Such self-in-
compatibility is normally a dominant trait, but selfing of self-compatible
plants has resulted in segregation of self-incompatible genotypes. Thompson
(1983) proposed a scheme for the production of a self-compatible
three-way-cross hybrid of *B. napus* utilizing recessive self-incompati-
ability. A major drawback of the scheme is the difficulty of producing
commercial quantities of selfed seed on the self-incompatible parent lines.
Thompson suggested growing plants in polyethylene tunnels in which dry
ice (carbon dioxide) was placed twice a week during the flowering time to
increase CO$_2$ concentrations in the air, which increases seed set on self-
incompatible strains. This method has not yet been used commercially.

FIELD- PLOT TECHNIQUES FOR GENOTYPE EVALUATION

In the major Brassica oilseed breeding centers of Canada and Europe,
research plots are planted with power-driven multiple-row seeders. The
seed is delivered evenly to the drill runs with a belt-cone seed dispenser
(Fig. 12-9). Both single and multirow belt-cone dispensers are used. The
multirow belt-cone is equipped with an electronically driven distributor to
ensure that all rows receive the same amount of seed. Most seeders are
equipped to dispense fertilizer and insecticide to each row.

At harvest in Canada and Europe, *B. napus* plots are cut, left to dry
naturally in the field for 5 to 10 days, and threshed with a plot combine. *B.
campestris* plots are either threshed directly with a plot combine or cut,
dried, and threshed in the same manner as the *B. napus* plots (Fig. 12-10).
Seed from the combine is passed over a field scalper to remove chaff,
placed in labeled paper or cotton bags, and dried at 35 to 38 °C until the
moisture content of the seed is below 8%. The seed yield of each plot is
Figure 12-9  (A) Multiple-row belt-cone seed dispenser showing plastic enshrouded cone (a) and belt (b). Seed is dispensed through the opening left by the curve in the belt (c), to an electronically driven distributor (d) which ensures each row receives an equal quantity of seed. (B) Bank of six single-row belt-cone seed dispensers for sowing single-row plots. The cones and belts are ground driven through a zero-max gear box (z) to provide an infinite selection of row lengths. Hoppers dispense metered amounts of fertilizer (f) and insecticide (i) to each drill run.
recorded, and a subsample of seed is cleaned on a Dakota blower or similar cleaning device in preparation for analysis of oil and protein quantity and quality.

For early-generation evaluation, each genotype is sown in a single-row plot 3 to 6 m long with 60 cm between rows. Check cultivars are sown every fifth to tenth row. If the soil conditions are highly variable or if a more precise evaluation of a trait is desired, the proportion of checks may be increased or the experiment may be replicated two to three times. If a very large number of lines are to be evaluated, only selected ones may be harvested. Plants of selected lines are cut, laid at the end of the row, and threshed as the plot combine moves down the alley between ranges.

Breeding material undergoing precise yield evaluation is commonly sown at a single location in four- or six-row plots 6 m long with rows spaced 30 cm apart. This row spacing facilitates manual weed control at the two to four true-leaf stage. Prior to harvest, a 30-cm section is cut and discarded from each end of the plot. With four-row plots, all rows are harvested, while in six-row plots, the two outside rows are left standing to protect the cut plants from being blown by the wind, and also may be used to assess susceptibility of mature plants to shattering.

In winter-rape evaluations, the harvesting and selection techniques
must be very efficient because nurseries cannot be harvested until late July or early August and new seedlings must be planted in mid to late August. Unexpected delays can result in the loss of a year in the breeding cycle.

Since the early 1970s, all potential cultivars considered for release in western Canada have first been grown for evaluation by domestic crushers. The company or institution that owns the candidate cultivar supplies to the chosen crushers sufficient seed to sow some 350 to 400 ha. The crushers contract with producers to plant the required area and return all production for processing. Depending on the size of the oil extraction plant, the seed is sufficient for one to several days of full-scale crushing. The results of the commercial crush are made available to researchers and the industry. Such large-scale tests are conducted a year before the general release of a new cultivar. They enable the identification of any major weaknesses of the cultivar in quality or processing traits before the cultivar enters major commercial production. The cost of the commercial-scale test is borne by the crushing industry, while research on the resulting oil and meal is usually funded by the Canola Council of Canada.

For early evaluation of strains with new oil or protein characteristics, approximately 1 t of seed is processed through a small-scale extraction facility at the P.O.S. Pilot Plant Corporation at Saskatoon, Saskatchewan, Canada. The resulting products are evaluated under research contracts with the Canola Council of Canada.

PROCEDURES FOR SEED PRODUCTION

Methods for Producing and Maintaining Breeder Seed

Breeder or prebasic seed is genetically the purest source of a cultivar. It is critical that breeder seed be maintained and reproduced with the utmost care and attention of the breeder. Ironically, it is on research farms that proper land histories, isolation of production areas, and clean harvesting equipment are likely to be the most difficult to obtain because numerous potential cultivars are under multiplication at the same time. Thus, contract production with highly qualified seed growers is frequently utilized.

Regulations for the production of breeder seed must be followed. The crop must be inspected by the appropriate federal or state inspector for genetic purity and the absence of weeds. In Canada, breeder seed plots normally are sown in rows 60 cm apart to allow roguing for off-types and
weeds. A sample of the seed harvested or of reserve seed is used to sow future breeder seed multiplication plots.

In Europe, methods for maintaining *B. napus* cultivars are more complex because the cultivar must meet narrow standards for uniformity, stability, and distinctness. Because the certification system in the European Economic Community (EEC) considers *B. napus* to be a largely self-pollinating crop, breeders must produce a uniform and homozygous cultivar. Cultivars commonly are maintained by selfing single plants, growing progeny rows, eliminating any off-type rows, and bulking the remaining rows to produce breeder seed. Although the uniformity restrictions of the EEC for *B. napus* cultivars are not as strict as for completely self-pollinated crops, the level of uniformity required in Europe is much greater than for other producing regions of the world.

Before the introduction of the EEC regulations for certification, maintenance of *B. napus* cultivars in Europe often was combined with a continuous upgrading of the cultivar. Because the cultivars were heterogeneous populations that varied in many characteristics, single plants were selected, progeny tested, and the best lines bulked to form a new elite breeder seed lot for the cultivar. A classical example of this work was given by Loof (1974) for the Swedish winter *B. napus* cultivar ‘Matador.’ The oil yield of the cultivar was increased by 15% over nine cycles of selection during breeder seed production.

The maintenance of *B. campestris* cultivars follows a similar scheme to that of *B. napus*, but the requirements for cultivar uniformity, stability, and distinctiveness are less stringent because all *B. campestris* cultivars are heterogeneous populations.

Because the *Brassica* oilseed crops have a high multiplication rate of more than 1000:1, only two generations of multiplication from breeder seed is required to reach commercial quantities. In both Canada and Europe, 90% or more of the commercial crop is sown with certified seed.

In Canada, breeder seed is distributed to experienced members of the Canadian Seed Growers’ Association (CSGA) who produce foundation seed for their own use or for sale to other seed growers or return it under contract to the owner of the cultivar. The foundation seed is sold or contracted to members of the CSGA who produce the certified seed. All records are maintained by the CSGA. In addition to meeting germination and purity standards, all foundation seed of canola cultivars must be submitted for erucic acid and glucosinolate analysis. Any seed failing to meet the given quality standards established for that cultivar is not eligible for that class. In Europe, the seed company owning the rights to the cultivar contracts with selected seed growers to buy back all basic (foundation) seed produced from breeder seed.
FUTURE PROSPECTS FOR CULTIVAR DEVELOPMENT

Because the available genetic variation in *Brassica* species is extensive, further improvements are possible. Indeed, the prospects are even more exciting now than they were 40 years ago.

The development of canola-quality *B. juncea* cultivars will increase the *Brassica* oilseed hectarage in many traditional growing regions, and will also allow expansion into new production areas. Under the growing conditions of western Canada, *B. juncea* outyields the best *B. napus* cultivars by 20% (Woods, 1986). *B. juncea* also is well adapted to areas of Australia, Spain, and the United States. Another mustard species, *B. carinata*, also has considerable untapped potential as an oilseed crop. Hybrid cultivars of *B. napus* hold promise for significant yield increases, and hybrid cultivars of *B. juncea* may soon follow.

The production of doubled-haploid derived lines by anther or microspore culture is now available as a routine technique to rapidly produce large numbers of homozygous lines from many *B. napus* and from some *B. juncea*, *B. carinata*, and *B. campestris* genotypes (Keller and Armstrong, 1983; Chuong and Beversdorf, 1985; Seguin-Swartz et al., 1983). Such inbreds can be used to produce hybrid or pure-line cultivars, except in the self-incompatible *B. campestris* species. Thompson (1979) developed the *B. napus* summer cultivar ‘Maris Haplona’ and the winter strain RD49 by doubling the chromosome complement of naturally occurring haploid plants from the Canadian low erucic cultivar ‘Oro’ and the Swedish cultivar ‘Victor.’ Both doubled-haploid selections outyielded their parent cultivars by 11 to 12%. The doubled-haploid technique reduces the population size required to recover gene combinations occurring at low frequencies. However, artificial production of doubled haploids is labor intensive, and the value of the doubled-haploid technique has yet to be demonstrated in a large-scale breeding program.

Protoplast fusion within *B. napus* has resulted in the successful combining of two cytoplasmically inherited traits: male sterility and triazine tolerance (Pelletier et al., 1983). Schenck and Robbelen (1982) have successfully fused protoplasts of the two diploid species *B. campestris* and *B. oleracea* to produce new *B. napus* germplasms. Protoplast fusion also may allow the transfer of genes between distantly related species or genera. Embryo-rescue techniques are increasing the success rate of many interspecific crosses designed to transfer important characteristics between species. The usefulness of variation induced through the application of somaclonal techniques is still unclear, although Sacristan (1982, 1985) has reported selection of blackleg resistant *B. napus* plants using such a procedure. Gene transfer into *Brassica* oilseed plants by vectors, micro-injection, or electroporosis is still under development but holds
promise for incorporating valuable genes for characteristics such as herbicide tolerance.

The *Brassica* oilseeds have responded to biotechnology manipulation better than almost any other major crop plant. Except for their small and largely unmapped chromosomes, they could serve as a model biotechnological system. It is within *Brassica* oilseeds that the effectiveness of many techniques of biotechnology will be determined in a practical breeding program. There is a danger, however, that scarce resources available for conventional breeding programs may be transferred to the more glamorous and publicized activities related to biotechnology, with serious consequences to crop improvement in the short and medium term.

Despite the excitement and publicity surrounding biotechnology and hybrid cultivars, the essential base for cultivar improvement remains the conventional breeding approach. A strong conventional program is required to provide much of the variation upon which new cultivars will be based. Agronomically useful cultivars are needed to incorporate innovations from biotechnology or wide crosses. For example, a gene for herbicide tolerance is of little value unless it is incorporated into a superior cultivar.

A well-managed conventional breeding program still has the highest potential for future cultivar development. The utilization of modern seeding and harvesting equipment, which allows the evaluation of many progeny rows with only a small field crew, plus the availability of computer-assisted laboratory equipment, such as near-infrared reflectance spectroscopy (NIR), nuclear magnetic resonance (NMR), gas-liquid chromatography (GLC), and high-pressure liquid chromatography (HPLC), provide the breeder with powerful tools to rapidly identify superior phenotypes. Indeed, it may be that conventional cultivars produced by hybridization, in combination with improved selection techniques, may be able to compete with hybrid cultivars because of the specialized nature and high costs of hybrid seeds.

The overall breeding objective has been to make *Brassica* oilseeds more valuable and versatile to producers and the market. Great strides have been made toward this objective over the past 40 years and even greater achievements are possible in the next 10 to 15 years. The ultimate goal of making *Brassica* oilseeds and their products premium commodities is well within reach of today's breeders.

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