

Genetic Improvement of Red Cabbage: Opportunities for Nutrition, Productivity and Resilience

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Introduction:

Red cabbage (*Brassica oleracea* var. *capitata* f. *rubra*) is more than a colourful vegetable. Its characteristic red-purple colour is mainly associated with **cyanidin-based anthocyanins**, while its nutritional value also includes glucosinolates, vitamin C and other bioactive compounds. For plant breeders, these characteristics create an opportunity to develop cultivars that combine **productivity, nutritional quality, attractive colour and**

environmental resilience. Studies have demonstrated substantial genetic variation among red-cabbage genotypes. Strauch et al. (2019), for example, characterized **27 red-cabbage genotypes** over two growing seasons and identified **29 anthocyanins**, predominantly acylated and glycosylated cyanidin derivatives. Three distinct anthocyanin profile groups were identified, indicating useful diversity for breeding and selection.

Trait	Reported evidence	Breeding implication
Red-cabbage genetic diversity	27 genotypes evaluated	Provides diverse material for parent selection
Anthocyanin diversity	29 anthocyanins identified	Opportunity to select superior pigment profiles
Anthocyanin concentration	1,111–1,780 mg Cy3G/100 g DM	Wide variation among cultivars
Acylated anthocyanins	Some cultivars contained $\geq 30\%$ diacylated pigments	Useful for colour stability
Glucosinolates	11 GSLs detected in cabbage lines	Scope for nutritional-quality breeding
Total GSL	Mean 10.6 $\mu\text{mol/g}$ DW	Demonstrates substantial phytochemical variation
Vitamin C	Up to 129.9 mg/100 g FW in a red-cabbage line	Potential target for nutritional enhancement
Anthocyanin genes	88 Bo anthocyanin biosynthetic genes identified	Molecular basis for marker-assisted improvement

Table 1- Sources: Ahmadiani et al., 2014; Park et al., 2014; Strauch et al., 2019; Han et al., 2021

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Why breed red cabbage?

Traditional breeding has largely emphasized **head size, compactness, maturity and yield**. Modern breeding can broaden these objectives by incorporating nutritional and molecular traits.

The new breeding equation

High yield + Nutritional quality + Stable colour + Stress resilience = Improved red-cabbage cultivar

This multi-trait approach is particularly relevant because nutritional compounds are not genetically fixed at a single level. Their expression can vary with **genotype, maturity and growing environment**.

Anthocyanins: The colour with breeding value

Anthocyanins are the principal pigments responsible for the attractive red-purple appearance of red cabbage. Their value extends beyond appearance because they are important phytochemicals and have applications as **natural food colourants**. Ahmadiani et al. (2014) evaluated seven red-cabbage cultivars at two maturity stages and reported anthocyanin concentrations of approximately **1,111–1,780 mg cyanidin-3-glucoside equivalents/100 g dry matter**. Cultivar and maturity influenced both pigment profile and colour characteristics.

Importantly, acylated anthocyanins are relatively more stable than non-acylated forms.

This makes red cabbage particularly interesting not only for fresh consumption but also as a source of natural colourants. Strauch et al. identified **29 anthocyanins** across 27 genotypes, with predominantly acylated cyanidin derivatives.



Figure – represent the anthocyanin pigment in Red cabbage

Breeding opportunity

Instead of selecting simply for **dark purple colour**, breeders can select for:

- ☞ Total anthocyanin concentration
- ☞ Desired anthocyanin profile
- ☞ Higher proportion of stable acylated pigments
- ☞ Stable colour across environments
- ☞ High head yield and market quality

From phenotype to gene: molecular breeding enters red cabbage

The genetic basis of anthocyanin accumulation is becoming clearer. Han et al. (2021) identified **88 anthocyanin biosynthetic genes** in *B. oleracea*. Their functional analysis indicated important roles for **BoMYB113.1** and **BoMYBL2.1** in

regulation of anthocyanin accumulation. This opens the possibility of combining conventional selection with:

**Phenotyping → Molecular markers →
Candidate genes → Genomic selection →
Superior cultivar**

Such approaches can reduce dependence on visible colour alone and help breeders identify promising material at earlier stages.

Nutrition should become a breeding objective

Red cabbage contains several classes of bioactive compounds. In a study of 45 cabbage lines, Park et al. (2014) detected **11 glucosinolates, 13 anthocyanins and 22 free amino acids**. Considerable variation occurred among lines, demonstrating the potential for nutritional-quality selection.

Glucosinolates are particularly important in *Brassica* breeding because their composition is genetically controlled but also influenced by environmental conditions.

Molecular breeding approaches are increasingly being investigated to manipulate desirable glucosinolate profiles.

Therefore, future red-cabbage selection should consider:

**Yield + Anthocyanins +
Glucosinolates + Vitamin C + Consumer
quality**

rather than yield alone.

Genotype × environment: the hidden challenge

One important consideration is that a genotype with high nutritional value in one environment may not necessarily perform similarly elsewhere. Research involving red-cabbage varieties has shown that anthocyanin profiles can vary with **genotype and vegetation period**. Five varieties evaluated under different production periods showed significant differences in anthocyanin profiles and antioxidant capacity. Therefore, **multi-environment testing** should be an essential component of breeding programmes.



Figure 2 – mature Red cabbage

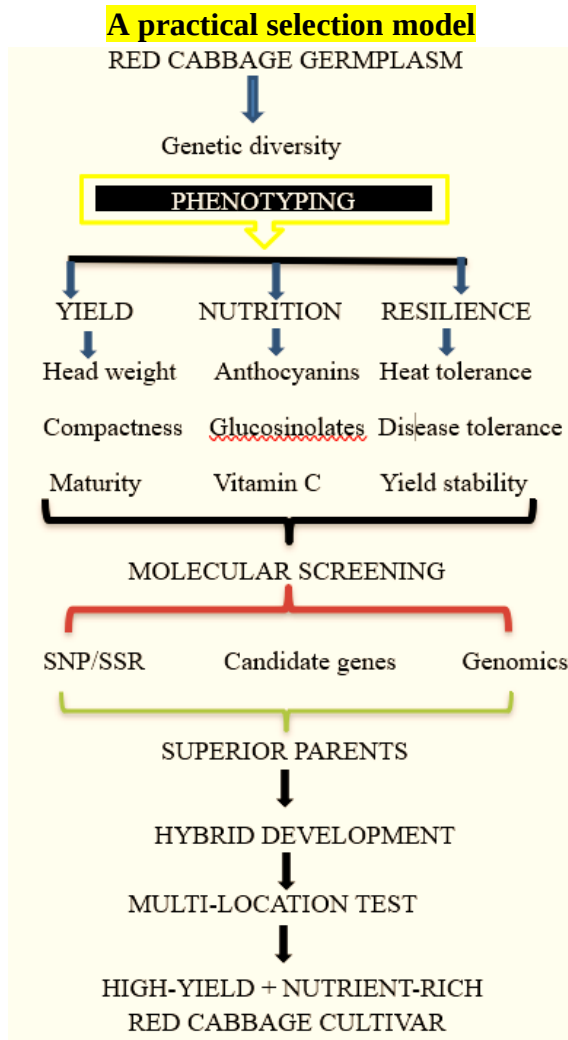


Figure 1. Proposed integrated breeding pathway for genetic improvement of red cabbage

Doubled haploids: speeding up cultivar development

The development of genetically uniform parental lines is an important step in hybrid breeding. **Doubled haploid (DH) technology** can accelerate the production of homozygous lines compared with repeated generations of selfing. Research in *B. oleracea* has demonstrated the value of DH-based material in hybrid breeding and combining-

ability studies. Singh et al. (2019) evaluated CMS and DH-based *B. oleracea* progenies for heterosis and combining ability, illustrating the potential of these materials for developing superior hybrids. For red cabbage, DH technology can therefore support rapid fixation of desirable combinations such as:

High yield + compact head + intense colour + high anthocyanins + stress tolerance

An important breeding target: stable anthocyanin production

An interesting finding from earlier field research is that anthocyanin productivity can also be affected by **environment and agronomic conditions**. Piccaglia et al. (2002) reported anthocyanin yields exceeding **90 kg ha⁻¹** in red cabbage under experimental conditions but also observed substantial differences between sites and years.

This highlights a key breeding challenge:

A good red-cabbage genotype should not only produce high anthocyanin levels—it should maintain desirable pigment production under different environments.

Thus, stability should become a measurable breeding trait.

What could the red cabbage of the future look like?

The ideal future cultivar should not be selected only because it is **“more purple.”**

Instead, breeders should aim for a genotype with:

- ☞ High yield
- ☞ High anthocyanins
- ☞ Desirable glucosinolates
- ☞ High vitamin C
- ☞ Stable colour
- ☞ Compact and uniform heads
- ☞ Disease and climate resilience
- ☞ Stable performance across environments

integrate germplasm diversity, precise phenotyping, biochemical analysis, molecular markers, doubled haploids, hybrid breeding and multi-environment testing.

The goal is simple:

“Breed red cabbage not only for colour, but for yield, nutrition, stability and resilience.”

Table 2-Future breeding priorities

Priority	Target trait	Preferred breeding approach
1	High head yield	Conventional selection + heterosis breeding
2	High anthocyanin content	Biochemical screening
3	Stable purple-red colour	Anthocyanin profiling
4	Desirable glucosinolate profile	Metabolomics + molecular breeding
5	High vitamin C	Nutritional screening
6	Disease/stress tolerance	Multi-environment selection
7	Stable performance	G × E analysis
8	Faster line development	Doubled haploid technology
9	Early molecular selection	SNP/SSR markers
10	Targeted trait improvement	Genomics and future gene-editing approaches

This represents a shift from **single-trait selection to integrated nutritional and climate-smart breeding.**

Conclusion

Red cabbage possesses considerable genetic and biochemical diversity that can be exploited for cultivar improvement. Variation in anthocyanins, glucosinolates and vitamin C provides measurable targets for nutritional breeding, while molecular studies are beginning to reveal genes underlying anthocyanin accumulation. The next generation of red-cabbage breeding should

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