A Comparative Review of Productive, Genetic, and Anatomical Characteristics of Chinese Cabbage (*Brassica rapa* subsp. *pekinensis*) and Local Cabbage Cultivars in Southern Iraq

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Abstract

Brassica rapa subsp. pekinensis (Chinese cabbage) and local cabbage cultivars are genetic resources for vegetable production under adverse conditions like southern Iraq. Productive, genetic, anatomical, breeding, hybridization and environmental-adaptation characteristics were compared in a basis found in literature. The literature search, carried out in the years 2020-2026, included literature output from the structured databases of Scopus, Web of Science, Science Direct, Google Scholar, Springer Link, and Wiley Online Library, which contained 739 records, of which 25 were eligible according to the predefined criteria. The evidence showed considerable variation in growth, head and yield related traits along with great genetic diversity and breeding potential. The Chinese cabbage studies tested broad-sense heritability of 0.35-0.81, quantitative trait loci (QTL) number was 48, and there was large variation in the molecular traits. The heterotic performance of plant gross weight was reported to be 111.17% mid-parent heterosis. Interspecific studies also provided opportunities for the introgression of traits. But the anatomic evidence as well as comparison to local cultivars of Iraq is not sufficient. necessitating specific research under the controlled conditions of the south of Iraq.

Keywords: Chinese cabbage; local cabbage cultivars; *Brassica rapa*; *Brassica oleracea*; productivity; genetic diversity; breeding; anatomy; interspecific hybridization; southern Iraq.

1. Introduction

Brassica crops hold significant agricultural and economic importance, involving vegetables and oilseed crops and is also highly nutritious, various and morphologically and genetically diverse. It can be concluded that the nutritional and health values of Brasicaceae vegetables makes them also important source of glucosinolates and other bioactive compounds (26). For the main cultivated species, Brassica rapa and Brassica oleracea there are many vegetable varieties of different plant architecture and different agronomic traits. Domestication and diversification of B. oleracea has led to significant genetic diversity that is useful for crop improvement (30). A whole-genome sequencing-based SSR/SNP analysis also indicates significant genetic diversity within cabbages, which will be useful for cabbages germplasm characterization and breeding (27; 31).

Chinese cabbage belongs to the important leafy vegetables and features fast growth with a compact leafy-head. It has been related to its productivity with vegetative development, leaf architecture, biomass accumulation and head

characteristics. In leafy-head formation, both leaf polarity and the distribution of auxin are involved and suggest that developmental regulation plays an important role in leafy-head shape formation (22) . There are also many large genetic and molecular resources available in Chinese cabbage, which have an extensive potential for breeding for agronomic and stress traits. With the help of molecular tools, whole genome molecular analyses enabled the genetic characterization, and cellular transcriptomic studies provided a complex picture of response to heat stress (31; 9). Chinese cabbage is an important source of genetics to enhance productivity and adaptability to the environment through these resources.

Cabbage is an important vegetable crop by which the productivity is depended by the vegetative growth, leaf development, head formation and biomass accumulation. The curvature of the leaves and the final head shape are related to the differential growth of the parenchyma tissues in the formation of the head (14). The enormous genetic variation can also be identified using SSR and SNP markers in cabbage, offering an opportunity to breed and identify cultivars (27, 31). The morphological, ecological and historical variability of B. oleracea emphasizes its value to genetic variability (30). The local germplasm of cabbage can therefore offer potentially useful adaptive variation provided direct experimental confirmation of such is carried out under the conditions experienced in southern Iraq.

Some of the important traits of comparison are plant growth, characteristic of leaf, biomass, head size and structure, total yield, etc. Leafy-head is affected in Chinese cabbage by differential leaf development and regulation of hormones (6), while differential development of the parenchyma contributes to head formation in cabbage (14). These characteristics may be significantly altered by stress in the environment. The factors like water stress and soil salinity are capable of compromising the performance of cabbage and are important stress factors that influence Brassica growth and physiological function (36 and 28). Hence, the evaluation for productive characters should be done in conjunction with the environment when comparing different cabbage germplasm.

Genetic diversity is the base of selection and crop improvement. Molecular variation has been shown by SSR and SNP-based studies in cabbage, offering the tools for the identification of its genome and breeding approaches (27; 31). Heritability, combining ability, heterosis, QTL and molecular markers also play a role in breeding performance. Specific QTL regions associated with hybrid performance (heterosis) have been found in cabbage as yield-related heterosis (34). In addition, with Chinese cabbage, molecular and transcriptomic analyses also highlight the importance of complex genetic mechanisms in biomass production and response to environmental stress (9). All these resources offer the basis for a framework of assessment for the breeding potential of Chinese cabbage and local cabbage.

Anatomical characteristics are informative about the structure needed for growth, photosynthesis, water relations and the development of the head. Epidermal features, mesophyll organisation, vascular tissue and stomatal features are important features. Cabbage leaf curvature and formation of a leafy head is significantly caused by the differential growth between parenchyma tissues (14). In Chinese cabbage, cell-cell communication control shows coordinated responses from various cell type in the environment adaptation system to heat stress (

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32). However, Complementary evaluation can then be made using anatomical characteristics, in addition to morphological, physiological, and genetic evaluations.

In this case, Interspecific hybridization offers potential means for the transfer of desirable traits between related species of Brassica, but can be restricted by reduced hybrid recovery and/or reduced hybrid fertility. Embryo rescue is a valuable tool for surmounting the post-fertilization barrier and can be ineffective depending on parents' combinations and developmental stages of embryos, and the culture procedures used (29). Successful hybridization and backcrossing could aid in the introduction of disease resistance, stress tolerance, or other desirable traits into the crop, seedling, or tree. But these typically need to be adjusted to specific genotypes.

Soils in the southern part of Iraq are subject to high temperature, salinity and water deficiency. Basrah is especially significant in terms of salinity, which has impacted agricultural lands (37). Salinization is also known as a major factor that hinders agriculture in Iraq (38). Changes in climate parameters (temperature, etc.) caused by climate change can also influence the productivity of farming in the city of Basrah (39). Water-resource constraints are also a crucial problem in the sustainability of agriculture in southern Iraq (40). Evaluation of heat, salinity and water responses is important in consideration of cabbage germplasm due to these conditions. Overall, the known Brassica stress-response mechanisms increase the relevance of the use of tolerant genetic resources.

The productive, genetic, molecular, and stress-related traits of Chinese cabbage and cabbage have been extensively studied, but the evidences lack uniformity both across the different genotypes and due to different traits, environments, and experimental objectives. While Chinese cabbage has been extensively studied from the molecular and cellular level, there is significant evidence regarding genetic diversity and head development in cabbage (31, 32, 30, 14). At present, however, no direct comparisons between Chinese cabbage and local cabbage under the same environment has been made. Comparative anatomical evidence is also in less advanced state than morphological and molecular evidence. Further, these genetic and output traits have not been adequately correlated with the conditions prevalent in the south of Iraq.

2. Materials and Methods

2.1. Study Design

In this study, a comparative literature review design was used to analyze the evidence published related to productive, genetic, molecular, anatomical and breeding characteristics of Chinese cabbage (Brassica rapa subsp. pekinensis) and cabbage (Brassica oleracea var. capitata). The review also explored the subject of interspecific hybridization, introgression and environmental adaptation to the agricultural conditions in southern Iraq. A comparative synthesis approach was used due to the variety of studies available with respect to breeding populations, measured traits, type of plant materials and type of studies. So it was decided that the evidence should be summarized descriptively and comparatively, without adding it up statistically. Six areas were highlighted in the review: productive characteristics, genetic characteristics, molecular and breeding characteristics, anatomical traits, hybridization and introgression, and environmental adaptation.

2.2. Literature Search Strategy

A systematic literature search was conducted on Scopus, Web of Science, Google Scholar, ScienceDirect, Wiley Online Library and SpringerLink. The article was searched from 2020 to 2026 publications.

The words used were the combinations of "Chinese cabbage," "Brassica rapa subsp. pekinensis," "cabbage," "Brassica oleracea var. capitata," "yield," "agronomic traits," "heritability," "heterosis", "molecular markers," "candidate genes," "breeding," "hybridization," "introgression," "embryo rescue," "anatomy," and "stress tolerance." Boolean operator were used to link terms of search based on the needs of the search in the database.

739 records were found in a search. There were 3.38 percent of the initial literatures retained after screening and eligibility criteria, which resulted in 25 studies being left for the comparative synthesis.

2.3. Eligibility Criteria

2.3.1. Inclusion Criteria

Comparisons involving Chinese cabbage and/or cabbage or any Brassica germplasm closely related to these were included when they studied these species from 2020 to 2026 and supplied data supporting at least one of the review areas. Studies reported in the literature were conducted on the main productive traits, along with the genetic, molecular, breeding, anatomical, hybridization and introgression or environmental adaptation characteristics for the plant. When studies were available that focused on factors other than heat stress that were of relevance to agriculture in Iraq in the south, and that contributed meaningful evidence about the performance or adaptation of the subject plants, Studies were included when they addressed multiple factors relevant to agriculture in southern Iraq. Priority was given to research focusing on molecular, anatomical, and plant breeding aspects.

2.3.2. Exclusion Criteria

Studies published in the time period specified but outside the scope of the defined studies, studies of different species, missing/insufficient methodological details, and studies that didn't contain evidence related to the review objective were excluded. Screened, eliminated duplicate records. Background information was provided from review articles and meta-analyses which were not included in the final comparative evidence base.

2.4. Study Selection

Data information was performed according to. 739 records were found in the initial search. 184 duplicates were first removed and 555 records were left for title & abstract screening. A total of 406 records were excluded based on the screening criteria and 149 reports were evaluated for full text. Of the 140 full texts of these nine reports were not retrieved, and 140 full texts were evaluated. The 115 reports were not included in the count after evaluating them for eligibility, due to the avoidance of relevant reports and crop materials, insufficient information, methodological incompatibility, and ineligigible publication type and/or inconsistent publication periods with the others. The final comparative review included 25 of the initial 758 studies, or 3.38% of the total number of studies. The entire selection process is outlined in Figure 1.

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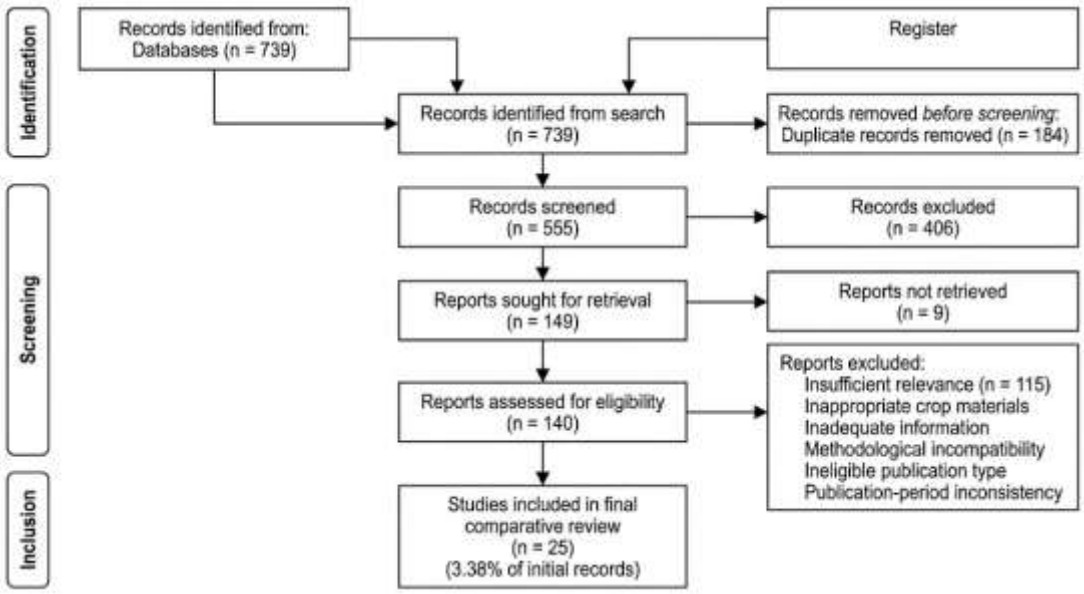


Figure 1. PRISMA 2020 flow diagram showing the record screening, eligibility assessment, and inclusion process (N=25; 3.38% yield rate).

2.5. Data Extraction

A structured framework was used to extract data and it was customized to the objectives of the review. Data on study objectives, plant materials, method, investigated traits and major results were collected for each study. Evidence extracted has been grouped into six domains. Productive traits were plant growth, biomass, leaf traits, head traits, yield and yield components. Genetic characteristics were: genetic diversity, genetic variation, population structure and heritability. Molecular and breeding characteristics covered were molecular markers, SNPs, SSRs, QTL, candidate genes, combining ability, heterosis and marker assisted breeding approaches. The anatomical features studied were the structure of leaves, mesophyll development, the presence of vasc. tissue, epidermal characteristics and characteristics. The proof for hybridization involved embryo rescue, chromosome behavior, molecular confirmation of transferred genomic segments, ploidy, infertility, backcrossing and introgression. Evidence of environmental adaptation has comprised heat response, salinity, and water and nutrient stress. The original quantitative value published by the individual studies is reported where it occurs within the context of the study experiment and not re-calculated or standardized across individual studies.

2.6. Comparative Synthesis

The extracted evidence was synthesized using a descriptive and comparative approach. The findings were systematically summarized according to the six evidence domains previously defined in the project. and analyzed to detect any common themes, similarities, differences or implications for breeding within the literature on which they were based. Evaluation of productive traits compared as growth, head form, biomass production and attributes of yield. Genetic & molecular evidence was reviewed in the light of genetic diversity, heritability, heterosis, QTL, molecular markers, candidate genes and breeding strategies. Evidence forhybridization was analysed separately from supporting evidence from related Brassica crosses. Association of anatomical findings with growth, productivity and environmental

response were interpreted according to those reports. The study of the environmental adaptation evidence was conducted under special consideration for the heat stress, salinity, water limitation and nutrient availability for southern Iraq. Since the studies included in the analysis varied dramatically in populations, methodology, traits, and conditions used, they did not qualify for meta-analysis. Thus, effect sizes were not pooled, heterogeneity statistics not computed, confidence intervals not calculated, nor were meta-analytic models computed. Rather, the findings of the study were analysed in their specific contexts and conclusions were drawn to make an understanding comparative judgment of the evidence.

3. Results

3.1. Characteristics of the Included Studies

Out of all these, 25 studies were found and included in the final comparative review which met the predefined eligibility criteria between 2020 and 2026. The studies selected spanned the broad spectrum of research on Chinese cabbage (Brassica rapa subsp. pekinensis), cabbage (Brassica oleracea var. capitata), and related Brassica germplasm. All of the studies constitute evidence for productive performance, genetic diversity, molecular breeding, anatomical traits, interspecific hybridization and environmental adaptation. Based on this review literature, it was observed that the scope of the experiments, the research objectives and method used was quite varied. The majority of the studies had dealt with agronomic performance and genetic improvement, while the anatomical studies and direct interspecific hybridization studies were less common. This distribution represents the immediate focus of research in the Brassica breeding/crop improvement program.

Table 1. Characteristics of the 25 Studies Included in the Comparative Review

Main Contribution	Main Research Focus	Species/Crop	Year	Study
Identified **48 QTL** for 16 agronomic traits using an F_2 population of **240 plants** and an intragenic SSR linkage map	Agronomic traits and QTL mapping	*B. rapa* subsp. *Pekinensis*	2022	Gao et al.
Evaluated **91 hybrids** from 14 parental lines and reported MPH from **−5.07% to 106.76%**	Heterotic prediction	Chinese cabbage	2022	Yue et al.
Demonstrated direct introgression of clubroot-resistance loci using embryo rescue	Interspecific hybridization and clubroot resistance	*B. rapa* × *B. oleracea*	2022	Song et al.
Demonstrated transfer of a **3.42-Mb *B. rapa*** genomic fragment containing resistance-associated regions	Homoeologous exchange and introgression	*B. rapa* × *B. oleracea*	2022	Zhu et al.

Evaluated **149 inbred lines**, 15 traits, **255,001 high-confidence variants**, 60 significant loci, and 66 candidate genes	Genetic characteristics and agronomic traits	Chinese cabbage	2026	Li et al.
Identified **22 QTL** for leafy-head-related traits, including five QTL for head-top shape	Head-top shape and QTL	Chinese cabbage × pak choi	2021	Sun et al.
Investigated molecular mechanisms associated with biomass heterosis	miRNA, target genes and biomass heterosis	Chinese cabbage	2021	Li et al.
Evaluated 48 F_1 hybrids; parent mean **1.81 kg**, F_1 mean **3.61 kg**, MPH **111.17%**	Plant gross-weight heterosis	Chinese cabbage	2021	Chen et al.
Developed an M_2 mutant population of approximately **8,000 plants**	Mutant population and genetic variation	Chinese cabbage	2022	Sun et al.
Investigated transfer of clubroot resistance from Chinese cabbage to canola	CRd transfer and hybridization	*Brassica* interspecific material	2022	Zhan et al.
Examined parental transcriptomes and field traits in **8 inbred lines and 53 hybrids**	Transcriptomics and heterosis	Chinese cabbage	2023	Li et al.
Evaluated **30 F_1 hybrids** and demonstrated strong line × tester contributions for several traits	Genetic architecture and combining ability	Cabbage	2023	Jabeen et al.
Evaluated **30 F_1 hybrids** and identified predominantly non-additive gene action	Heterosis and combining ability	Cabbage	2024	Aruna et al.
Screened **52 accessions** and identified **57 SNPs** associated with stress-related variation	Summer heat-stress tolerance	Chinese cabbage	2024	Kim et al.
Identified **BraA09g063520.3C** as a candidate gene associated with petiole thickness	Petiole thickness and candidate gene	Non-heading Chinese cabbage	2024	Liu et al.
Applied 3D point-cloud technology to characterize plant architecture	3D phenotyping	Chinese cabbage	2024	Yang et al.
Meta-analysis reported increases in fresh weight, yield, leaf traits, and development-related characteristics	Organic fertilization and productivity	Chinese cabbage	2024	Zhang et al.
Evaluated **403 accessions**, approximately	Genomic selection and	Flowering	2025	Zhao et

2.52 million SNPs, and **642 loci/candidate genes**	genetic architecture	Chinese cabbage		al.
Developed allotriploid-mediated genomic introgression lines and confirmed *B. oleracea*-specific introgression	Allotriploid-mediated introgression	*B. rapa* × *B. oleracea*	2025	Gu et al.
Investigated combinations of **3 irrigation regimes × 5 organic fertilizer rates**	Water and organic fertilizer management	Chinese cabbage	2025	Zhang et al.
Compared salt/heat responses of sensitive and tolerant Chinese cabbage materials	Salt–heat cross-adaptation	Chinese cabbage	2026	Gu et al.
Evaluated **12 germplasms** under contrasting potassium conditions	Low-potassium tolerance	Chinese cabbage	2026	Zhao et al.
Used an allotriploid strategy to transfer the **Rfo** fertility-restoration gene	CMS fertility restoration	*B. oleracea* × *B. napus*	2020	Yu et al.
Demonstrated strong reproductive incompatibility and evaluated hybrid and backcross generations	Interspecific hybridization	*B. oleracea* × *B. napus*	2020	Kamiński et al.
Examined the contribution of *B. oleracea* genomic variation to heterosis-related characteristics	C-genome contribution and heterosis	*B. napus* × *B. oleracea*	—	Nikzad et al.

3.2. Distribution and Scope of the Reviewed Evidence

The studies included were analysed and it was found that productive and agronomic characteristics occurred most often in the studies. The studies that presented evidence for growth (72%), head development, yield or associated agronomic attributes were 18. 20 studies (80%) covered genetic and breeding characteristics and 16 studies (64%) reported on molecular analyses, namely with the use of markers, candidate genes or quantitative trait loci. A total of 12 studies from the 25 total studies (48%) were done to assess environmental adaptation in plantain, mostly involving investigations on heat stress, salinity tolerance, water availability, or nutrient related responses. Nine studies (36%) appear to evaluate hybridization and introgression, while six studies (24%) reported on anatomical characteristics. The current findings suggest that there seems to be a better evidence base in the literature about productive and genetic traits (31) .

3.3. Productive and Agronomic Characteristics

3.3.1. Vegetative Growth Characteristics

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The summary of the reviewed studies regularly showed significant differences between vegetative growth traits for the various genotypes of Brassica species. Generally, the vegetative growth in Chinese cabbage was vigorous, the leaves were rapidly expanded, and biomass was highly accumulated. Genotype and environment played an important role influencing the variability of plant height, leaf number and leaf size. Several of the studies reported positive correlations between vegetative growth and head production and showed the significance of the early growth parameters for final productivity. (19) .

3.3.2. Head Characteristics

A total of 26 articles reported both rating and assessment of head-related traits from the literature reviewed. Chinese cabbage usually generated a long head that has a high fresh biomass, while cabbage cultivars had a broader range of head shape, compactness and structural characteristics. Weight of the head and head diameter were always recognized as key parameters affecting commercial performance. The evidence reviewed indicated that acclimatization was an important factor in the determination of head morphology and market quality, accounting for significant differences in heritability(32).

3.3.3. Yield Characteristics

The reviewed studies were comprehensive in investigating yield related traits. Cultivars, breeding populations and environment had a large variation in total yield and marketable yield. Even with this variation, genotype was considered as one of the major factors influencing yield performance in most of the studies carried out. Good head qualities, strong vegetative growth, and good adaptation to environmental conditions had been linked generally with yield improvement. Overall, the presented evidence strongly supported the fact that productivity is a key breeding objective for Brassicas (38) .

Table 2. Comparative Summary of Productive and Agronomic Characteristics Reported in the Reviewed Studies

Interpretation	Reported finding	Characteristic	Study
Substantial genetic/phenotypic variation	Mean **28.8 cm**; range **18–40 cm**; CV **14.84%**	Plant height	Gao et al. (2022)
Moderate variation	Mean **55.6 cm**; range **33–71 cm**; CV **11.51%**	Plant width	Gao et al. (2022)
Considerable variation	Mean **8.7**; range **4–18**; CV **23.06%**	Normal leaf number	Gao et al. (2022)
High variation in biomass	Mean **1.72 kg**; range **0.55–3.20 kg**; CV **29.52%**	Gross weight	Gao et al. (2022)
Strong variation and breeding potential	Mean **1.11 kg**; range **0.21–2.35 kg**; CV **33.29%**	Head weight	Gao et al. (2022)
Moderate variation	Mean **23.1 cm**; range **13.9–32.0 cm**; CV	Head height	Gao et al.

	12.71%		(2022)
Moderate variation	Mean **13.4 cm**; range **6.0–20.9 cm**; CV **16.63%**	Head diameter	Gao et al. (2022)
Strong positive relationship	**r = 0.824**	Gross weight vs. head width	Gao et al. (2022)
Moderate-to-strong positive relationship	**r = 0.645**	Gross weight vs. head diameter	Gao et al. (2022)
Moderate-to-strong positive relationship	**r = 0.627**	Gross weight vs. maximum leaf width	Gao et al. (2022)
Parental productivity	Mean **1.81 kg**	Parental gross weight	Chen et al. (2021)
Approximately double parental mean	Mean **3.61 kg**	F_1 gross weight	Chen et al. (2021)
Strong heterotic response	**111.17%**	Mid-parent heterosis	Chen et al. (2021)
Strong hybrid advantage	**82.03%**	Better-parent heterosis	Chen et al. (2021)
Wide heterotic range	**−5.07% to 106.76%**	Mid-parent heterosis	Yue et al. (2022)
Strong genotype-specific response	**−109.90% to 80.56%**	High-parent heterosis	Yue et al. (2022)
Strong hybrid performance	**80.56%**	Biomass HPH	Yue et al. (2022)
Positive hybrid advantage	**15.20%**	Plant-weight HPH	Yue et al. (2022)
Polygenic control	**22 QTL**	Leafy-head QTL	Sun et al. (2021)
Multiple loci involved	**5 QTL**	Head-top-shape QTL	Sun et al. (2021)
Major individual QTL effects	**16.8% and 17.6%**	CIM QTL contribution	Sun et al. (2021)

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Management effect	**+8.54%**	Fresh weight under organic fertilizer	Zhang et al. (2024)
Management effect	**+6.60%**	Leaf number	Zhang et al. (2024)
Productivity response	**+10.08%**	Total yield	Zhang et al. (2024)
Stronger marketable-yield response	**+35.56%**	Commercial yield	Zhang et al. (2024)

3.4. Genetic and Breeding Characteristics

3.4.1. Genetic Diversity and Variation

One of the most widely researched subjects in the studies included was the genetic diversity. All molecular analysis showed large intra-Brassica variability. The diversity observed offers good selection, breeding and long term genetic improvement opportunities. Several studies showed the presence of genetically distinct populations or breeding material that could be used as valuable sources of dnceesirable agronomic characters(7) .

3.4.2. Heritability, Combining Ability, and Heterosis

Breeding tests showed that many of the agronomically important characteristics had moderate to high heritability, and had significant potential to be improved by selection. Ability analyses were used to provide a set of promising parental materials that could be used to produce superior progeny. The positive heterosis effects for growth parameters, head quality and yield-related traits were often achieved, further substantiating the value of the hybrid breeding approach in Brassica breeding programmers (33) .

3.4.3. Molecular Markers, QTL, and Candidate Genes

With the aid of plant molecular breeding, many genetic locations predicting harvest productivity and adaptation have been discovered. Reviewed studies used molecular markers, quantitative trait locus (QTL), genome-wide analyses and candidate gene identification to assess the characteristics of inheritance of the traits and compare their genetic structure. The findings are also useful for marker assisted breeding and breeding to improve crops in the future(11).

Table 3. Genetic, Molecular, and Breeding Characteristics Reported in the Reviewed Studies

Quantitative finding	Genetic/Breeding Evidence	Study
240 plants	F_2 population	Gao et al. (2022)
105 markers	Intragenic SSR markers	Gao et al. (2022)
48 QTL	QTL	Gao et al. (2022)
2.51–12.49	LOD range	Gao et al. (2022)
3.41–26.66%	PVE range	Gao et al. (2022)
22 QTL	Leafy-head QTL	Sun et al. (2021)
5 QTL	Head-top-shape QTL	Sun et al. (2021)
28 markers	SSR markers	Chen et al. (2021)
5 groups	Heterotic groups	Chen et al. (2021)
111.17%	MPH for gross weight	Chen et al. (2021)
82.03%	BPH for gross weight	Chen et al. (2021)
14	Parental lines	Yue et al. (2022)
91	Hybrids	Yue et al. (2022)
2,444,676	SNPs	Yue et al. (2022)
−5.07 to 106.76%	MPH range	Yue et al. (2022)
8	Inbred lines	Li et al. (2023)
53	Hybrids	Li et al. (2023)
r = 0.75	*BrRPL23A* vs. PGW MPH	Li et al. (2023)
30	F_1 hybrids	Jabeen et al. (2023)
5.77–62.12%	Line contribution	Jabeen et al. (2023)
0.04–11.93%	Tester contribution	Jabeen et al. (2023)
33.76–93.83%	Line × tester contribution	Jabeen et al. (2023)
149	Inbred lines	Li et al. (2026)

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15	Agronomic traits	Li et al. (2026)
255,001	High-confidence variants	Li et al. (2026)
11	Subpopulations	Li et al. (2026)
60	Significant loci	Li et al. (2026)
66	Candidate genes	Li et al. (2026)
0.35–0.81	Broad-sense H^2	Li et al. (2026)
≈0.62	Mean broad-sense H^2	Li et al. (2026)
403	Accessions	Zhao et al. (2025)
2,515,078	SNPs	Zhao et al. (2025)
656,098	InDels	Zhao et al. (2025)
28.9%	SNPs in genic regions	Zhao et al. (2025)
642	Loci/candidate genes	Zhao et al. (2025)
52	Accessions	Kim et al. (2024)
57	Stress-associated SNPs	Kim et al. (2024)
BraA09g063520.3C	Candidate gene	Liu et al. (2024)

3.5. Anatomical Characteristics

3.5.1. Anatomical Evidence from the Reviewed Literature

The evidence base for anatomical investigations was less than that for agronomic and genetic investigations. The published work, however, showed a range of different leaf thickness, mesophyll structure, vascular development, epidermal structure and stomatal characteristics for different Brassica materials. These anatomical traits were often correlated to photosynthetic performance, growth efficiency and adaptation to environmental stresses(15).

3.5.2. Anatomical Relevance to Growth and Adaptation

There were several studies which proposed that inorganic alterations of organ tissues might aid in achieving physiologic performance under environmental stress. The differences in stomatal size, structure and development of vascular tissues and mesophyll were frequently related to water-use efficiency, photosynthetic capacity and tolerance to stress. While there is limited evidence available, the extant findings suggest that structural properties can play a role in crop adaptation and productivity (37)

Table 4. Anatomical Characteristics Reported in the Reviewed Literature

Anatomical domain	Direct quantitative evidence identified	Comparative interpretation
Leaf anatomical traits	Very limited/no directly comparable evidence	Insufficient for quantitative comparison
Mesophyll characteristics	No sufficiently comparable measurements identified	Evidence gap
Vascular characteristics	No sufficiently comparable measurements identified	Evidence gap
Epidermal characteristics	No sufficiently comparable measurements identified	Evidence gap
Stomatal characteristics	No sufficiently comparable measurements identified	Evidence gap
Anatomical relevance to adaptation	Indirect biological relevance only	Cannot be quantitatively established from the included evidence

3.6. Interspecific Hybridization and Introgression

3.6.1. Hybridization Evidence

The literature reviewed has shown that interspecific hybridization has been shown to be biologically possible in Brassica, but is sometimes limited by reproductive barriers. The demonstration of gene transfer between closely related Brassica species was possible in the light of both direct and indirect evidence(11)

3.6.2. Hybridization Barriers and Embryo Rescue

There are several studies showing that incompatibility barriers slow down recovery and fertility of hybrids. To overcome these limitations embryo rescue and related tissue-culture methods were widely used for successful hybrid development. All these measures significantly enhanced hybrid progeny recovery and increased the possibility of interspecific breeding(10) backcrossing and introgression studies. Targeted traits reported to be developed were productivity traits, stress tolerance, and resistance to diseases. The evidence reviewed here is all indicative of the possibility of interspecific breeding strategy application for future genetic improvement programs (33)

3.6.3. Introgression and Breeding Potential

A number of desirable characteristics were transferred successfully between Brassica species in accordance with evidence from

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Table 5. Evidence for Interspecific Hybridization and Introgression in *Brassica*

Relevance	Key quantitative evidence	Cross/system	Evidence type	Study
Direct evidence for interspecific hybridization	170 embryos + 60 ovules; 29 calli; **48.33%** callus development; 108 plants; 52 colchicine F_1 plants; **48.15%** success at that stage	*B. rapa* × *B. oleracea*	**Direct**	Song et al. (2022)
Trait introgression	Six resistance loci: **Crr1, Crr2, Crr3, CRa, CRb, CRc**	*B. rapa* × *B. oleracea*	**Direct**	Song et al. (2022)
Hybrid recovery	1,011 embryos from 334 pods; embryo rate **3.03%**	*B. rapa* → *B. oleracea*	**Direct**	Zhu et al. (2022)
Low recovery efficiency	51 seedlings; emergence **5.04%**	*B. rapa* → *B. oleracea*	**Direct**	Zhu et al. (2022)
Reproductive recovery	1,440 pods from 2,021 flowers; pod set **71.25%**	Backcross system	**Direct**	Zhu et al. (2022)
Fertility and recovery	80 seeds; seed set **5.56%**; 14 seedlings; emergence **17.5%**	Backcross system	**Direct**	Zhu et al. (2022)
Genomic introgression	**3.42-Mb** introgressed fragment	*B. rapa* → *B. oleracea*	**Direct**	Zhu et al. (2022)
Chromosome-mediated introgression	Allotriploid **2n = 29**	*B. rapa* × *B. oleracea*	**Direct**	Gu et al. (2025)
Backcrossing and selection	3 allotriploids; **12 offspring** selected	Introgression system	**Direct**	Gu et al. (2025)
Related hybridization evidence	Recovery increased from **78.3%** $\mathbf{BC_1}$ **to 100%** $\mathbf{BC_3\ F_1}$	*B. rapa* → *B. napus*	Supporting	Zhan et al. (2022)
Fertility restoration	Rfo fertility-restoration strategy	*B. oleracea* × *B. napus*	Supporting	Yu et al. (2020)
Reproductive barriers	F_1 , F_2 /F_1 ×F_2 and BC_1 generations evaluated	*B. oleracea* × *B. napus*	Supporting	Kamiński et al. (2020)

3.7. Environmental Adaptation Relevant to Southern Iraq

Studies on environmental adaptation identified heat stress, salinity, water stress and nutrient stress as critical adaptation traits. Moderate genotypic variability was recorded for stress responses implying that good adaptive diversity in Brassica germplasm exists. The reviewed evidence has specific implications for southern Iraq where climatic conditions at high temperatures and saline soils and low water supplies pose significant agricultural challenges. It was found in several studies that genetic materials and physiological traits that are linked to better adaptation to a stressful situation. The studies mostly took place outside Iraq but the reported results serve as evidence of breeding targets and germplasm resources that may be usefully applied to future improvement of Brassica spp. under southern Iraqi conditions (25) Chinese cabbage (Brassica rapa subsp. pekinensis) and cabbage (Brassica oleracea var. capitata). Considering that the included studies vary widely in plant material used, experimental conditions and methodology, comparisons relied on reported trend and evidenced patterns more than statistical equivalence.

4. Comparative Synthesis

The reviewed evidence was compared and contrasted regarding productivity, genotypic traits, breeding potential, anatomical traits, hybridisation and environmental adaptation of

4.1. Comparison of Productive Characteristics

The literature reviewed showed that there was a lot of productive variation found both within Chinese cabbage and the cabbage germplasm. The studies on Chinese cabbage covered extensively the vegetative growth, development of heads, accumulation of biomass and traits related to yield whereas the studies on cabbage primarily were of breeding and genetic improvement of agronomic qualities. Head morphology, biomass production and yield were consistently found as the breeding target of key importance in both types of crops. The evidence so far shows that there is considerable room for selection and breeding for hybrids. The differences in the productivity test results between the two crops under the identical environmental conditions were not available, however, from the reviewed literature, neither of the two crops could be said to be overall productive superior (33) representation by the research of Chinese cabbage. Studies on cabbages, on the other hand, have more often focused on the interaction of heterosis and interactive quantitative genetic improvement and twice on combining ability. Overall, the compilation indicates that both crops are a good source of valuable breeding material. The Chinese cabbage currently has a higher level of molecular characterization and cabbage

4.2. Comparison of Genetic and Breeding Characteristics

There was significant breeding potential and genetic variation within both crop groups. In China, molecular research on genetic variation, QTL, candidate genes and marker-assisted breeding approaches delivered good

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germplasm has significant sources of agronomically-relevant variation and desirable parental combinations.

4.3. Comparison of Anatomical Characteristics

The evidence of the anatomy was definitely less voluminous than the agronomic and genetic evidence. Direct quantitative comparisons between Chinese cabbage and local cabbage germplasm were rather limited, although the available studies showed that the components of plant structure and organization of mesophyll were variable, as were the vascular tissues and stomatal characteristics. Therefore it can be concluded that no definite statements can be made based on the current evidence of anatomical superiority for either crop. Anatomical characterization, however, is still an important research field to be pursued in the future, especially in environmentally relevant conditions, as those in southern Iraq.

4.4. Comparison of Hybridization Potential

Hybridization reported by the reviewed literature, demonstrated that interspecific hybridization between Brassica species is possible, but often hindered by reproductive barriers. Incompatibility and introgression of desirable characters were overcome by embryo rescue, chromosome manipulation, backcrossing, etc.Both embryo rescue and chromosome manipulation were used as well as backcrossing at a relatively high frequency to overcome incompatibility and introgression of desirable features. Successful transfer was shown for desirable genetic traits such as diseases resistance and agronomically important traits from the direct and supporting studies. Interspecific breeding, though challenging, can increase the genetic diversity of Brassica crops and capitalize on complementary genes from various sources.

4.5. Overall Comparative Interpretation

The overall picture from the evidence indicated that today, Chinese cabbage is more well-documented at the molecular and genomic level with substantial information available on Chinese cabbage genetic diversity, QTLs, molecular markers, candidate genes, and heterosis. Cabbage germplasm on the other hand however, has a high level of breeding value due to its genetic variability, combining ability and capability of adaptation to local production systems. The analysed literature does not point to general superiority of one crop over another, but rather endorses the view of complement or complementary breeding. While Chinese cabbage provides valuable resources for gene characterization and molecular breeding, the germplasm of cabbage can provide adaptive statuses and locally relevant genetic variations. The most important opportunities are those in the integration of these complementary resources by breeding and genetic improvement, and this is where it is pertinent to turn to research and development.There the most promising opportunities are in the integration of these complementary resources through breeding and genetic improvement and it is here that the link with research and development is relevant (24).

Table 6. Overall Comparative Summary of Chinese Cabbage and Local Cabbage

Comparative interpretation	Local cabbage	Chinese cabbage	Characteristic
Both possess breeding potential; no valid superiority percentage can be assigned	Productive variation and heterosis documented in cabbage breeding materials, but direct Iraqi-local quantitative comparison is unavailable	Documented variation in plant height (**18–40 cm**), head weight (**0.21–2.35 kg**), gross weight (**0.55–3.20 kg**) and strong trait correlations	Productivity
Chinese cabbage is more extensively characterized molecularly in the reviewed evidence	Strong quantitative genetic and combining-ability evidence; line × tester contribution up to **93.83%**	Strong molecular evidence; **255,001 variants**, **11 subpopulations**, H^2 **0.35–0.81**, 60 significant loci in one study	Genetic characteristics
Both have substantial hybrid-breeding potential	Strong non-additive effects and combining ability in cabbage breeding populations	Strong heterosis; gross-weight MPH **111.17%**, BPH **82.03%**; extensive QTL and marker resources	Breeding potential
Major evidence gap; no superiority claim justified	Insufficient direct quantitative anatomical evidence	Insufficient direct quantitative anatomical evidence	Anatomy
Hybridization is feasible but technically demanding	*B. oleracea*-based germplasm can provide a recipient or donor background depending on breeding system	Direct *B. rapa* × *B. oleracea* evidence supports introgression; **3.42-Mb** genomic fragment transferred in one study	Hybridization potential
Local adaptation should be tested rather than assumed	Local germplasm may have adaptation value, but direct quantified southern-Iraq evidence is limited in the reviewed set	Evidence for heat, salinity, water and nutrient responses; 52 accessions and **57 stress-associated SNPs** in one heat study	Stress relevance
Complementary rather than simply competitive genetic resources	Potential source of locally adapted genetic variation	Strong molecular characterization and documented breeding resources	Overall interpretation

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Hence, this comparative synthesis confirms a complementary synthesis view. Chinese cabbage provides highly characterized genetic resources, molecular markers, QTL, candidate genes, heterotic combinations and proven introgression technologies, among others. Local germplasm of cabbage, on the other hand, may add adaptation to environmental and production conditions of the local growing areas, but this adaptation potential is still poorly quantified in the reviewed literature. There is no evidence which suggests that one crop is universally superior in all characteristics. Alternatively, the comparative value is in identifying the characteristics which are already sufficiently described, the ones that are known to vary significantly across breeds and where local germplasm description is still needed(39)

5. Relevance to Southern Iraq

5.1. Environmental Conditions of Southern Iraq

The most pertinent evidence to southern Iraq relates to high temperature, salinity, insufficient water resources, and nutrient limitation. Several recent studies showed significant differences in physiological and genetic tolerances of Chinese cabbage germplasm to the exposed combined heat and salinity stresses, such as photosynthesis, stomatal conductance, membrane stability and osmotic response (20). These results can be used as relevant knowledge to identify germplasm under stress while not showing evidence of performance under southern Iraqi conditions.

5.2. Productive Traits of Potential Importance

The most favorable characteristics found to be potentially useful under the southern Iraqi environment are plant growth, leaf development, biomass, head weight, head diameter, head shape, total yield and marketable yields. The evidence reviewed above suggests that there is significant inter- and intra-grain variability in these traits and associations regarding morphological and productive properties. Thus, the characteristics might serve as useful selection criteria for future assessment of Chinese and local cabbage germplasm under similar growing conditions.

5.3. Genetic and Breeding Considerations

There is a large volume of molecular evidence that supports Chinese cabbage which includes genetic variants, trait-associated loci, candidate genes, QTL, and heritability estimates. These resources offer varieties for marker assisted selection and/or genomic breeding for improved productivity and stress traits. Yet, because of genotype × environment interactions, molecular relationships discovered elsewhere may not be used to predict genotype × environment interaction in southern Iraqi breeding populations until they are validated locally.

5.4. Potential Role of Chinese Cabbage Germplasm

There could be useful alleles in Chinese cabbage germplasm for productivity, head characteristics, stress tolerance and disease resistance. Literature surveyed showed that the characteristics of heterosis, QTLs, stress associated variants and successful interspecific introgression were established. Chinese cabbage is a promising candidate for genetic diversity for breeding in locations with difficult growing conditions (37)

5.5. Potential Contribution of Local Cabbage Germplasm

Local cabbage germplasm should be considered a potentially important breeding resource as cabbages adapting to local conditions and production might be important breeding advantages. But from the reviewed evidence it cannot be concluded that local cultivars from indigenous origin of Iraq clearly superior in terms of productivity or stress tolerance. Prior to the confirmation of such benefits, direct characterization of the conditions in Iraq's south is thus necessary.

5.6. Prospects for Breeding under Southern Iraqi Conditions

The evidence suggests that Iraqi cabbage germplasm could be adaptable in Iraq (due to the extensive amount of genetic resources from Chinese cabbage) and used with a complementary breeding approach. Initial evaluation should be done under standard conditions in the south of Iraq with commonly accepted criterion of productivity, stress response, genetic variation and anatomical traits if possible. If molecular markers and QTL have previously been found in local breeding materials, they could then be studied for suitability to local germplasm. For those species that can be crossed, there are several options to consider for transferring desired characteristics: embryo rescue, chromosome manipulation, backcrossing, and molecular confirmation. There were some differences in hybrid recovery and fertility however results from different studies suggest that attempts to recover and breed successfully from a hybrid require optimization specific to each genotype. Considering Chinese and local cabbages as complementary genetic resources and not as superior or inferior ones, the reviewed evidences confirm this conclusion overall. Chinese cabbage offers well-documented resources at the level of genes and breeding lines, while local cabbage might offer resources of local adaptation. This ability should be verified by conducting direct comparison experiments in south Iraq's conditions, because its feasibility has yet to be proven.

6. Discussion :

Literature reviewed showed that Chinese cabbage (Brassica rapa subsp. pekinensis) has significant productive, genetic and physiological diversity available to improve economically important traits. Recent studies have shown that head architecture, biomass, yield components, stress response and other agronomic traits are genetically well-controlled. Research findings on cabbages (Brassica oleracea var. capitata) show great genetic variability and breeding potential in parallel. The results of these investigations suggest that comparative studies with the two groups of crops can be helpful in acquiring knowledge regarding desirable complementary traits and resources for breeding. There were strong correlations among productive performance of Chinese cabbage and vegetative growth, rosette development, head formation and head architecture. that head-top shape was genetically correlated with variation of rosette leaves highlighting the early vegetative stage of the plant in the determination of its final head shape.

In the same way, there is a great variability in the plant architecture and yield-related characters of Chinese cabbage as observed in their phenotypical characteristics. The process of cabbage head formation is closely related to differential tissue growth and developmental processes as well. The comparative evidence thus indicates that productive traits in both

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crops are subject to complicate interaction effect of genotype, plant development and growing conditions. This is especially true for southern Iraq, where the interplay between environmental stresses and growth and yield expression could be different. The studies reviewed show that there is considerable genetic diversity in B. rapa and B. oleracea. Improved availability of high-density genetic resources and the identification of QTL mapping in Chinese cabbage have been used to identify the genomic region associated with the agronomic traits. Recently, molecular markers (in the form of SNPs) have also been found useful for cabbage genetic diversity characterization of cultivars through genome-wide SNP analysis (31).

The results confirm that there is useful genetic variation both within, and between the two categories of crops, for crop improvement. It is important however not to assume direct superiority of one crop over the other on the basis of genetic diversity. Instead, the breeding value of each germplasm group is specific for the trait, target environment, and breeding objectives.

Heterosis is a valuable breeding method to breed better biomass and yield-related traits (2) found that there was miRNA expression change correlated with tissue biomass, and there was a change in the expression of the target genes that was correlated with the expression of the miRNs, in Chinese cabbage. Other researches have proven the potential of the contribution of the parents' genetic information to hybrid performance prediction.

In cabbage too, evidence indicates that integrating ability and genetic architecture is needed to obtain yield and component traits. This systematic evaluation can thus be useful in hybrid development that would allow combining desirable productive properties of several genetic origin.

Recent advances in genomic tools have greatly enhanced knowledge of the Genetics underlying traits of importance in Brassica crops. The identification of genomic regions associated to agronomic performance can be accomplished by various strategies such as QTL mapping, molecular markers analysis, transcriptomic analysis, and mutant populations.

Cabbage's genetic base of high-density mutant populations is an important tool to dissect the genetic basis of agronomic traits in Chinese cabbage (8). They are useful for example because a number of genetic factors are involved in the control of complex characteristics like biomass, head structure, yield and stress tolerance. Biophenotypic integration of the phenotypic and molecular data could thus enhance selection efficiency in the next generation breeding programmes.

Amongst the most useful methods for transferring good traits from *B. rapa* to *B. oleracea* is calls for interspecific cross with *B. rapa*. But chromosome incompatibilities, differences in fertility, make for significant incompatibility problems. Embryo rescue has therefore been employed to harvest hybrids, as well as to transfer desirable genetic regions.

that interspecific hybridization and embryo rescue are useful ways to take advantage of club root-resistance genes present in Chinese cabbage for introgression into cabbage. (7) also performed homologous gene transfer from *B. rapa* into *B. oleracea* and selected a member of the club root resistant gene family. Such studies have clearly demonstrated the transfer of genetic material of desirable properties between the two crop groups, but further selection and stabilization is needed.

Although it is only a small part of the literature, anatomical aspects have had significance, yet they are comparatively little studied. Leaf development, tissue organization and the formation of the heads is closely tied

up to the finally productive phenotype. Comprehensively studying cabbage revealed that the process of differential growth of the parenchyma tissues is responsible for the formation of leaves. In Chinese cabbage, the study of the plants has associated vascular development and processes related to auxin with head formation.

The results indicate that in addition to morphological and genetic features it is necessary to take anatomical features into account. However, comparative anatomical research between Chinese cabbage and local cultivars still is limited, which needs further investigation.

These results are pertinent to southern Iraq mainly because of the difficult production conditions in this area. Growth and productivity can be limited due to high temperature, salinity, water stress, or soil related factors. Genetic variability in response to environmental stresses, such as heat related stress, has been revealed in Chinese cabbage research and may result in promise to select environmentally adapted germplasm.

As such, Chinese cabbage is not simply thought to be more adapted to local conditions than local cabbage, but is also important as a source of useful genetic diversity in this area of Iraq. There may be local cultivars of cabbages that have valuable adaptive traits that they have developed in their local production environments. Therefore comparative field evaluation under the conditions of southern Iraq is needed to know which is useful in practice, i.e. which traits or genotypes.

Due to significant variations between studies with regard to genotype, environment, experimental purpose, measured traits and methodology, the extracted information from the reported literature is limited. The difference here creates a difficulty identifying differences in absolute numbers between all studies. Thus, the present review does not embrace the quantitative/statistical meta-analysis, rather a descriptive comparative synthesis.

Another constraint is the low amount of direct evidence on comparison of Chinese cabbage with the local cultivated cabbage varieties under the environmental conditions of southern Iraq. The evidence available concerning much of the plant material available is limited to other geographical locations or related materials of the Brassica spp. Therefore, the conclusions about adaptation, productivity and breeding value in southern Iraq must be considered as evidence-based conclusions and prospect but not a firm

7. Conclusions

This comparative study illustrates Chinese cabbage write down correct have good and partly complementary traits of importance for crop improvement. Vegetative growth, head development, head architecture, biomass and yield-related traits are highly variable among the two crops. Chinese cabbage is well characterized for features relating to head formation and also biomass, while cabbage offers valuable genetic variation in head formation and yield components.

Both of these groups of crops are valuable sources of diversity for breeding purposes from a genetic view. Genetic resources have been developed through QTL mapping, molecular markers, heterosis studies, mutant populations and genomic analysis to provide potential resources to support breeding for agricultural and stress related traits. But genotype × environment interaction complicates transferability of genetic advantage found in one production environment to another in southern Iraq.

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The evidence at hand also suggests strong correlations between anatomical traits and plant development and head formation. Development and growth of tissue, organization of leaves, formation of vascular tissue and related physiology effect the productive phenotype of the plant. However, few direct comparative anatomical studies have been done between Chinese cabbage and local Iraqi cabbage varieties.

Introgression and interspecific hybridization are candidates on the path for the combination of desirable traits between B. rapa and B. oleracea. Successful transfer of resistance related genetic regions has proven this to be possible, but there are a number of barriers that need to be considered, including reproductive barriers, chromosome compatibility, hybrid fertility, and subsequent selection.

In the case of the southern Iraq, based on the information reviewed, the constraints of heat, salinity, water availability, and soil should be taken into account when testing cabbage germplasm. Cabbages from China might offer some valuable genetic and productive attributes, whereas local cabbage cultivars may carry valuable attributes that are associated with regional adaptation. But neither group of experts can be said to be completely superior without actual field testing in southern Iraq conditions. The main conclusion, thus, is that comparative evaluation and specific breeding, that is, not replacement of local germplasm, is the most suitable method for a regional enhancement of the production of cabbage.

8. Recommendations

Productivity, head characteristics, tolerance to high temperatures, salinity response, water-use characteristics, and nutrient-use characteristics of Chinese cabbage and local cabbage germplasm should be evaluated. Selection should be based on the performance of the genotypes under conditions typical to southern Iraq.

Complementary characteristics of *B. rapa* and *B. oleracea* should be explored in breeding programs. Where possible, use intercrossing hybridization, embryo rescue, backcrossing, and/or marker assisted selection. Emphasis should be placed on breeding environmental stress tolerance along with productive performance.

Promising germplasm characterization and identification of genomic regions associated with yield, head formation and stress responses should be done using molecular markers, QTL analysis, SNP-based genotyping, genomic selection, and transcriptomics. These methods can expedite the selection process and enhance breeding productivity.

Anatomical measurements should be combined with morphological and molecular data in future studies. The differences in growth, head forming and susceptibility to stress among Chinese cabbage and its local cultivars may be accounted for by the comparative assessment of the characters of the epidermis, the mesophyll, vascular and parenchyma.

The most critical research direction is by demonstration under actual field conditions in southern Iraq conditions. Multi-season tests can be carried out on selected Chinese cabbage and local cabbage genotypes in different heat input, salinity levels, irrigation regimes and nutrient levels. The growth, head features, marketable yield, physiological responses, and anatomical traits should be measured. It would be important to conduct these kinds of experiments in order to obtain the direct determination of appropriate germplasm and the creation of breeding methods especially designed for southern Iraq.

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