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RESEARCH ARTICLE

A mutation in *BrPRPL1* causes leaf yellowing by influencing chloroplast protein translation in Chinese cabbage

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Highlights

- The large subunit ribosomal protein L1 of the chloroplast (*BrPRPL1*) is the candidate gene of *Mut298*.
- The silencing of *BrPRPL1* results in leaf yellowing of Chinese cabbage.
- A single nucleotide change from C to T in *BrPRPL1* significantly reduces the accumulation of chloroplast genome-encoded proteins RbcL, PsaA, and PsaB.

Abstract

Leaf color directly affects the appearance quality and nutritional quality of leafy vegetables, thereby determining their economic value. Here, we identified a golden leaf mutant, *Mut298*, from an ethyl methanesulfonate (EMS)-induced mutant library of Chinese cabbage. Through the approach of forward genetics, it has been demonstrated that the phenotype of *Mut298* is due to a single nucleotide substitution from C to T that changes glycine to arginine in the conserved domain of *BrPRPL1*, which encodes the large subunit ribosomal protein L1 of the chloroplast. Because the *PRPL1* mutation causes embryonic lethality in *Arabidopsis*, the function of *PRPL1* in leaf development remains elusive. In this study, the mutation of *BrPRPL1* causes a substantial reduction in the expression of key chloroplast-encoded proteins (RbcL, PsaA, and PsaB) and disrupts chloroplast development. Moreover, the chlorophyll content and photosynthetic parameters are significantly lower in *Mut298* plants than in wild-type plants, resulting in golden yellow leaves in Chinese cabbage. This study reveals the impact of *PRPL1* mutation on ribosome translation within chloroplasts and provides a theoretical a foundation for future research into the regulatory roles of *PRPL1* in plant growth and development.

Keywords: Chinese cabbage, mutant, chloroplast, gene function, ribosome translation

1. Introduction

Genetic variations in chlorophyll and carotenoid metabolic pathways lead to leaf yellowing in plants. In the chlorophyll biosynthesis pathway, the synthesis of 5-aminolevulinic acid (ALA) and the insertion of Mg^{2+} into protoporphyrin IX are two critical steps directly affecting chlorophyll synthesis (Wu *et al*. 2019). ALA, a common precursor for both chlorophyll and heme synthesis, is catalyzed by glutamyl-tRNA reductase (GluTR), while heme, as the end product, exerts feedback inhibition on GluTR activity (Zhao M H *et al.* 2020). A mutation in the heme oxygenase gene blocks heme degradation, leading to its accumulation. The elevated heme levels suppress ALA synthesis *via* negative feedback, impairing chlorophyll production and altering leaf color in pea (Linley *et al.* 2006). Magnesium chelatase is a key enzyme in chlorophyll synthesis, catalyzing the chelation of Mg^{2+} into protoporphyrin IX to form magnesium protoporphyrin IX (Papenbrock *et al.* 2000; Masuda 2008). In higher plants, this enzyme consists of three subunits: CHLI, CHLD, and CHLH (Zhao C *et al.* 2020). Mutations in *CHLI* and *CHLD* cause leaf yellowing in pea (Luo *et al.* 2013). Additionally, a

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single nucleotide mutation in *CHLI* reduces plastid-encoded polymerase activity, disrupting chloroplast development and chlorophyll biosynthesis in *Brassica napus*, leading to leaf yellowing (Zhao C *et al.* 2020). Under ABA treatment, *MdSnRK1.1* promotes *MdGLK1* protein degradation *via* the 26S proteasome. Consequently, *MdGLK1*-mediated transcriptional activation of *MdHEMA1* is attenuated, suppressing chlorophyll biosynthesis in apple (Yang *et al.* 2024). Under heat stress, the upregulated expression of *ABI5* enhances its binding to *PPH* and *PAO* promoters to activate their transcription. Furthermore, heat stress promotes the interaction between *ABI5* and *MYB44* as well as ubiquitin-mediated degradation of *MYB44*, thereby relieving *MYB44*'s transcriptional repression on *PPH* and *PAO* and ultimately accelerating chlorophyll degradation (Liu W K *et al.* 2023).

Carotenoids, primarily comprising yellow carotenes and orange xanthophylls, significantly influence plant organ coloration (Polivka and Frank 2010). Phytoene synthase (PSY), the rate-limiting enzyme in carotenoid biosynthesis, catalyzes the condensation of isopentenyl pyrophosphate to form phytoene (Cazzonelli and Pogson 2010). *PSY* expression levels directly regulate carotenoid content, thereby influencing leaf coloration (Zhao M H *et al.* 2020; Wang *et al.* 2021). Furthermore, phytoene desaturase (PDS) is another key enzyme in carotenoid metabolism. *PDS* silencing causes yellow fruit in tomato (Naing *et al.* 2019). Under high light intensity, the upregulation of *bHLH71-like*, *CaVDE*, and *LUT5*, combined with downregulated *ZEP* expression, enhances antheraxanthin and zeaxanthin accumulation. This ultimately induces leaf yellowing in pepper (Liu Z B *et al.* 2023).

Chloroplasts, essential organelles in green plants, are integral to various biological processes such as photosynthesis, pigment biosynthesis, and amino acid production (Fu *et al.* 2022). Their functional stability influences both chlorophyll synthesis and degradation and the coloration of plant leaves. Changes in chloroplast structure and function often correlate with leaf color variations, which makes leaf color mutants crucial for studying chloroplast dynamics (Zhao M H *et al.* 2020; Cheng *et al.* 2022). The chloroplast genome encodes approximately 120–130 genes, including those for photosystem I (*psa*), photosystem II (*psb*), the large subunit of ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) (*rbcL*), the cytochrome b6f complex (*pet*), NAD(P)H dehydrogenase (*ndh*), ATP synthase (*atp*), ribosomal RNA (rRNA), transfer RNA (tRNA), and ribosomal proteins (*rpl*, *rps*), among others (Wicke *et al.* 2011). Disruptions in these proteins' expression or function can inhibit chloroplast development, alter chlorophyll metabolism, and lead to diverse leaf color phenotypes (Kusumi *et al.* 2011).

Chloroplast ribosomes, derived from cyanobacteria, play a pivotal role in synthesizing proteins encoded by the chloroplast genome (Tiller and Bock 2014; Sun and Zerges 2015). These ribosomal proteins are essential for ribosome biogenesis, chloroplast protein biosynthesis, and early chloroplast development. Mutations in these proteins can lead to translational disorders, impairing chloroplast function and consequently affecting plant growth and development (Romani *et al.* 2012; Robles and Quesada 2022). For instance, the absence of specific plastid ribosomal proteins in *Arabidopsis* can cause various phenotypic effects ranging from embryonic lethality to reduced viability. Loss-of-function *Arabidopsis* mutants of *PRPL1* and *PRPL4* exhibit embryonic lethality, whereas *Arabidopsis PRPL11* mutants demonstrate non-lethal symptoms such as leaf yellowing and stunted growth, due to compromised mRNA translation and photosynthesis (Pesaresi *et al.* 2001; Romani *et al.* 2012). Similarly, a mutation in *SVR8*, which encodes the chloroplast ribosome large subunit L24 in *Arabidopsis*, leads to defects in chloroplast rRNA processing and altered leaf color (Liu *et al.* 2013). The impact of these proteins on seedling development was first observed in maize (*Zea mays* L.), where the *Hcf60* mutation that affects the plastid ribosome small subunit protein PRPS17 significantly reduces photosynthesis and plastid translation levels, resulting in light-green seedlings (Schultes *et al.* 2000). *PRPL1* is essential for *Arabidopsis* embryo development. T-DNA knockout of *PRPL1* results in embryonic lethality, primarily attributed to disrupted fatty acid biosynthesis-a critical process for maintaining membrane integrity, signaling, and enzymatic regulation (Romani *et al.* 2012). This lethality stems from disrupted chloroplast translation of *accD*, which encodes the β subunit of heteromeric acetyl-CoA carboxylase (ACCase), the key enzyme converting acetyl-CoA to malonyl-CoA (Bryant *et al.* 2011).

Chinese cabbage is highly favored by consumers due to its rich nutritional value, high yield, storability, and ease of transportation (Chen *et al.* 2024; Wang *et al*. 2025). In a recent study, we identified a Chinese cabbage mutant, *Mut298*, through ethyl methanesulfonate (EMS) mutagenesis (Lu *et al.* 2016; Sun *et al.* 2022). Unlike the wild type, *Mut298* exhibits golden yellow leaves across the entire plant and shows retarded growth. Genetic analysis indicated that a single recessive mutation controls this leaf yellowing trait. The candidate gene responsible for the yellowing of Chinese cabbage leaves, *BrPRPL1*, was pinpointed using genome sequencing of bulked DNA (MutMap) and kompetitive allele-specific PCR (KASP). This gene encodes the chloroplast ribosomal large subunit protein L1. In the mutant line *Mut298*, a single nucleotide substitution from C to T changes glycine to arginine in the seventh exon of *BrPRPL1*. This specific alteration in Chinese cabbage leads to a dysfunctional ribosomal translation system. This dysfunction impairs chloroplast development, resulting in leaf yellowing and stunted growth. Identifying *Mut298* has revealed critical sites affecting *BrPRPL1* function in chloroplast development, offering valuable resources for Chinese cabbage breeding. Moreover, this study elucidates the effects of *PRPL1* mutation on chloroplast ribosome translation and establishes a framework for investigating *PRPL1*'s regulatory functions in plant growth and development. Currently, no studies have reported *PRPL1*'s involvement in regulating leaf color development in plants. Thus, our findings not only advance the understanding of *PRPL1*'s regulatory mechanisms in leaf color but also provide both theoretical foundations and genetic resources for breeding Chinese cabbage varieties with diverse leaf coloration.

2. Materials and methods

2.1. Experimental materials and cultivation conditions

We used the Chinese cabbage inbred line 'A03' (wild type,

WT) and the leaf yellowing mutant *Mut298*, derived from EMS mutagenesis of WT, as experimental materials. The M_5 homozygous mutant of *Mut298* was established after multiple generations of self-pollination. We performed crosses between *Mut298* and WT to produce F_1 and F_2 progeny. In August 2023, seeds were sown in a greenhouse at Hebei Agricultural University: 10 F_1, 30 WT, 30 *Mut298*, and 270 F_2 seeds. The physiological indicators of the fourth leaf, counted from inside to outside during the rosette stage (40 d after sowing), were measured. Samples were immediately frozen in liquid nitrogen and stored at –80°C for subsequent DNA, RNA, and protein analyses.

2.2. Genetic analysis of mutant phenotypes

Phenotypic evaluations were conducted for WT, *Mut298*, F_1, and F_2 plants. The segregation ratios for F_1 were calculated, and the F_2 were analyzed using a chi-square test to determine Mendelian inheritance.

2.3. Determination of physiological parameters

On the harvest day (14 d after sowing), the fresh weights of shoots and roots were measured. Subsequently, the samples were oven-dried at 180°C for 72 h to determine their dry weights. Twenty replicates were performed for each treatment. The total leaf area was assessed using LI-3100C (LI-COR Inc., Lincoln, USA). Leaf dry mass per area (LMA) was computed by dividing the leaf dry weight by the leaf area. Twenty replicates were conducted for each treatment. The superoxide anion and hydrogen peroxide contents in Chinese cabbage were determined using a plant superoxide anion staining kit (Servicebio Inc., Wuhan, China) and a plant hydrogen peroxide staining kit (Servicebio Inc., Wuhan, China), respectively. Chinese cabbage was grown in vermiculite for 5 d to measure root length, with thirty replicates per treatment.

Chlorophyll was extracted using the ethanol-acetone method (Liu *et al.* 2022). Specifically, we precisely weighed 0.2 g of fresh leaves and placed them into 50 mL centrifuge tubes, adding 10 mL of a 1:1 (v/v) ethanol-acetone solution. The leaves were extracted in darkness for 24 h until completely decolorized. Absorbance at 646 and 663 nm was measured using UV-1800 (Shimadzu Inc., Kyoto, Japan). Chlorophyll content was calculated using the following formulas:

Chlorophyll *a* (mg g^{-1})=$(12.21A_{663}–2.81A_{646})V/(1{,}000W)$

Chlorophyll *b* (mg g^{-1})=$(20.13A_{646}–5.03A_{663})V/(1{,}000W)$

where *V* is the volume of the extraction solution in mL and *W* is the leaf weight in g.

Net photosynthesis rate measurements were conducted between 9:00–11:00 a.m. on a clear day using LI-6800 (LI-COR Inc., Nebraska, USA) on the fourth true leaf from the inside out. For WT and *Mut298*, three seedlings (15 d after sowing) with consistent growth were selected, and PlantExplorer^{Pro+} (PhenoVation Inc., Wageningen, Netherlands) was used to measure chlorophyll fluorescence parameters in these seedlings.

2.4. Observation of chloroplast ultrastructure

The leaves of WT and *Mut298* were fixed and examined following the protocol described by Woodson *et al.* (2015). Ultrathin sections were prepared using a diamond knife on a Leica EM UC7 ultramicrotome (Leica Microsystems Inc., Buffalo Grove, USA). Chloroplasts were observed and photographed using a H7600 transmission electron microscope (Hitachi Inc., Tokyo, Japan).

2.5. Identification of the candidate gene through MutMap and KASP

DNA was extracted from 30 F_2 plants exhibiting the mutant phenotype and 30 F_2 plants with the WT phenotype using the CTAB method. Equal quantities of DNA from each phenotype group were pooled to create separate mutant and WT pools. These pools were then sequenced on an Illumina HiSeq 2500 platform (KeyLab Bio Inc., Guangzhou, China). The raw data were filtered to obtain high-quality reads, which were aligned with the V2.5 Chinese cabbage reference genome available at BrassicaDB (http://brassicadb.cn). SNP analysis was conducted, and candidate loci were screened with an SNP index≥0.8.

DNA was extracted from three *Mut298* plants, three WT plants, five F_2 plants with the mutant phenotype, and five F_2 plants with the WT phenotype. This was followed by sequencing analysis to exclude mutant genes that did not conform to the expected genotype-phenotype correlations. The primers for sequencing are presented in Appendix A. KASP was then used to identify the candidate gene among the remaining mutant genes.

2.6. Transcriptome analysis

Total RNA was extracted from the leaves at the same position from both WT and *Mut298* seedlings using TRIzol reagent (Thermo Fisher Scientific Inc., Waltham, USA). mRNA containing PolyA was isolated from the total RNA and subsequently fragmented at 94°C. cDNA synthesis was performed using SuperScript™ II Reverse Transcriptase (Invitrogen Inc., Carlsbad, USA) from the fragmented RNA. Second-stranded DNAs labeled with uracil were synthesized using DNA polymerase I and RNase H (NEB Inc., Ipswich, USA). The uracil-labeled (U-labeled) DNAs were then treated with UDG enzyme (NEB Inc., Ipswich, USA) to prepare for cDNA library construction. A cDNA library of approximately (300±50) bp was generated through PCR amplification. Sequencing was conducted using the Illumina NovaSeq 6000 system (LC-Bio Technology Inc., Hangzhou, China), producing 2×150 bp paired-end reads.

2.7. Virus-induced gene silencing (VIGS) of the candidate gene *BrPRPL1*

Functional validation of the candidate gene *BrPRPL1* was carried out using a TYMV-induced gene silencing method tailored for the Brassicaceae family (Hou *et al.* 2018). The VIGS vector was engineered by a biological company (GeneScript Inc., Nanjing, China). Plasmids with a high concentration (1,567 ng μL^{-1}) were prepared for the experiment. When WT plants developed two true leaves, they were selected for VIGS treatment. After observing phenotypic changes-the transition of leaf color from green to yellow in pTY-

BrPRPL1 plants-the plants were photographed and sampled. Quantitative RT-PCR (qRT-PCR) was employed to assess the silencing efficiency of *BrPRPL1*.

2.8. Western blot of chloroplast ribosome-encoded proteins

Leaves of WT, *Mut298*, and pTY-*BrPRPL1* were rapidly ground into a fine powder in liquid nitrogen and transferred to 2 mL centrifuge tubes. Each tube received 800 μL of protein lysis buffer (Beyotime Inc., Shanghai, China), followed by centrifugation at 12,000 r min^{-1} for 5 min. The supernatant was collected, and protein concentration was measured. The samples were then heated at 95°C for 10 min before loading 20 μg onto SDS-PAGE for electrophoresis to separate proteins.

Following SDS-PAGE, the proteins were transferred onto a polyvinylidene difluoride (PVDF) membrane (Beyotime Inc., Shanghai, China). The membrane was blocked in a blocking solution for 1 h at room temperature, then incubated with specific primary antibodies targeting actin at a dilution of 1:5,000 (v/v) (AT0004, Engibody Inc., Milwaukee, USA), RbcL at 1:2,000 (v/v) (A01110, Abbkine Inc., Wuhan, China), PsaB at 1:5,000 (v/v) (PHY0054A, PhytoAB Inc., California, USA), PsaA at 1:2,000 (v/v) (PHY0368A, PhytoAB Inc., California, USA), and PetB b6/f at 1:2,000 (v/v) (PHY0020S, PhytoAB Inc., California, USA). The secondary antibodies used were specific to mouse (BF03001X, Biodragon Inc., Suzhou, China) and rabbit (BA01235136, Bioss Inc., Beijing, China). Protein signals were detected using the Odyssey Infrared Imaging System (LI-COR Biosciences Inc., Lincoln, USA).

2.9. qRT-PCR analysis and subcellular localization

Total RNA was extracted from leaves at the same position from both WT and *Mut298* plants during the seedling stage and rosette stage, as well as from samples for transcriptome analysis using a total RNA extraction kit (Tiangen Inc., Beijing, China). Each sample included three biological replicates for both WT and *Mut298*, with three technical replicates for each biological replicate. Reverse transcription to synthesize first-strand cDNA for qRT-PCR was performed using a kit (Vazyme Inc., Nanjing, China). The ChamQ Universal SYBR qPCR Master Mix (Vazyme Inc., Nanjing, China) was utilized for qRT-PCR on a QuantStudio 5 System (Thermo Fisher Scientific Inc., Waltham, USA) under the following thermal cycling conditions: initial denaturation at 95°C for 2 min, followed by 40 cycles of 10 s at 95°C, 30 s at 60°C, and a final melt curve stage of 15 s at 95°C, 1 min at 60°C, and 15 s at 95°C. The relative expression levels of genes were quantified using the $2^{-\Delta\Delta Ct}$ method. Gene-specific primers for qRT-PCR are presented in Appendix A.

Protoplasts were extracted from Chinese cabbage and transformed according to Yu's method (Yu *et al.* 2024). The CDS sequence of *BrPRPL1* was cloned into the pMD18-T vector. The plasmid was then transformed into Chinese cabbage protoplasts using the PEG-mediated protoplast transfection method (Yu *et al.* 2024). GFP fluorescence signals were observed using a LSM900 (Zeiss Inc., Oberkochen, Germany). The primers for subcellular localization are presented in Appendix A.

2.10. Statistical analysis

SPSS Statistics 21.0 and Origin 2019 were used for data analysis and visualization, respectively. Physiological and qRT-PCR data were analyzed using Tukey's new multiple range test at $P \leq 0.05$ or *t*-test at $P \leq 0.05$.

3. Results

3.1. Morphology and chloroplast structure of WT and *Mut298*

Throughout the seedling and rosette stages, *Mut298* exhibited leaf yellowing and reduced growth rate compared to WT (Fig. 1-A and B). Transmission electron microscopy (TEM) revealed that chloroplasts in WT were ellipsoidal, well-developed, and neatly arranged with normally stacked granal lamellae, starch grains, and thylakoid grana (Fig. 1-C). In contrast, chloroplasts in *Mut298* were disorganized, less compact, displayed diminished starch grain accumulation, and indistinct thylakoid grana (Fig. 1-D). This indicated that the yellowing of the *Mut298* leaves is related to abnormal chloroplast development.

3.2. Physiological parameters of WT and *Mut298*

The shoot fresh weight and shoot dry weight of WT were significantly higher than those in *Mut298* (Table 1). However, the root length of WT was significantly lower than that in *Mut298* (Table 1; Appendix B). There was no significant difference between the imaging of superoxide anion and hydrogen peroxide (Appendix C). The yellowing of the *Mut298* leaves resulted in a significant reduction in chlorophyll content and photosynthetic parameters compared to the WT. Chlorophyll *a*, chlorophyll *b*, and net photosynthetic rate were significantly lower by 1.5-, 1.7-, and 0.5-fold, respectively, in *Mut298* than in WT (Fig. 2-A, B, and D). Chlorophyll fluorescence imaging revealed distinct differences between the WT and the *Mut298* mutant in terms of chlorophyll content and fluorescence parameters, including maximal quantum yield of PSII (F_v/F_m), photochemical efficiency of PSII in the light (F_q'/F_m'), and relative electron transport rate (rETR). Specifically, the chlorophyll imaging color for WT was yellow, in contrast to the blue color observed for *Mut298* (Appendix D), indicating lower chlorophyll content in *Mut298* (Appendix D). Fluorescence imaging for F_v/F_m and F_q'/F_m' in *Mut298* showed red, whereas WT displayed yellow (Appendix D), suggesting reduced F_v/F_m and F_q'/F_m' values in *Mut298* (Appendix D). Additionally, the rETR imaging showed *Mut298* in blue and the WT in red (Appendix D), indicating a lower rETR in *Mut298* (Appendix D).

3.3. Changes in chloroplast protein homeostasis and retrograde signaling

To explore the changes in gene expression levels related to metabolic pathways in WT and *Mut298*, seedling leaves were sampled for transcriptome analysis. The results showed that a total of 4,863 differentially expressed genes (DEGs) were identified between the two genotypes (Appendix E). GO enrichment analysis revealed that these DEGs are primarily enriched in biological processes associated with DNA transcription (Appendix F). KEGG enrichment

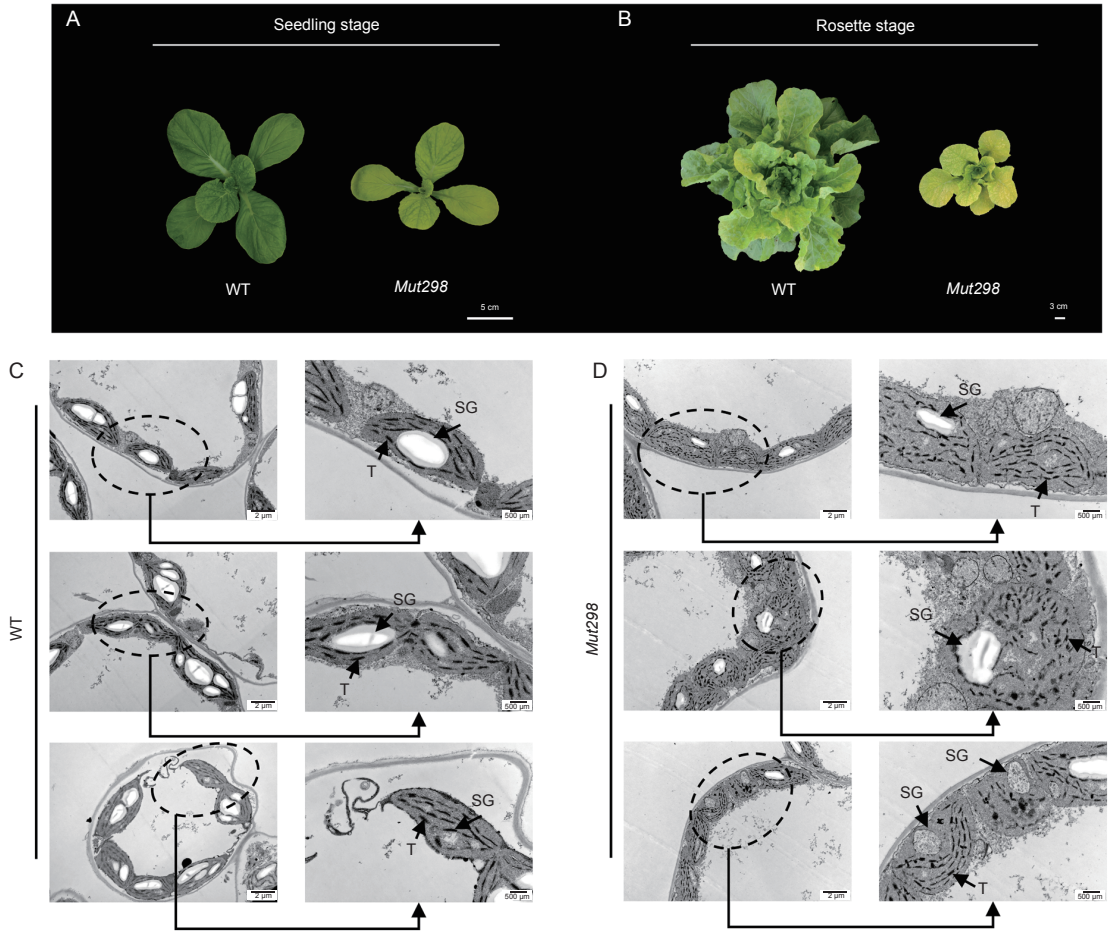


Fig. 1 Physiological indices of WT and *Mut298*. A, phenotypes of WT and *Mut298* plants at the seedling stage. B, phenotypes of WT and *Mut298* plants at the rosette stage. C, ultrastructure of chloroplasts in WT. T, thylakoid grana; SG, starch granule. D, ultrastructure of chloroplasts in *Mut298*. WT represents wild type of Chinese cabbage.

Table 1 Growth parameters of WT and *Mut298*[1)]

	SFW	RFW	SDW	RDW	RL	LA	LN	LWC	LMA
WT	4.328±0.970 a	0.156±0.072 a	0.388±0.126 a	0.011±0.002 a	4.717±0.288 a	22.177±4.583 a	7.000±0.725 a	0.91±0.018 a	17.824±5.724 a
Mut298	2.651±0.521 b	0.132±0.059 a	0.133±0.034 b	0.006±0.001 b	7.263±0.593 b	21.337±4.911 a	6.000±0.459 b	0.95±0.010 a	6.285±1.288 b

[1)] A total of 20 replicates were conducted for nine morphological and physiological indices, including shoot fresh weight (SFW), root fresh weight (RFW), shoot dry weight (SDW), root dry weight (RDW), root length (RL), leaf area (LA), leaf number (LN), leaf water content (LWC), and leaf mass per area (LMA). WT represents the wild type of Chinese cabbage.
The different letters in each column indicate significant differences between WT and *Mut298* at $P<0.05$, determined by *t*-test.

analysis revealed that the DEGs are mainly enriched in pathways related to plant hormone signal transduction (Appendix F). For the chloroplast retrograde signaling and chloroplast proteolysis that we are concerned with, there were a total of 25 DEGs associated with chloroplast retrograde signaling (Appendix G). Among them, eight DEGs were significantly downregulated and 17 DEGs were significantly upregulated (Fig. 3-A and C; Appendix G). All six DEGs (*EGY2*, *NANA*, *PreP1*, *FtsH6*, *FtsH11*, and *FtsH12*) related to chloroplast proteolysis were significantly upregulated (Fig. 3-B; Appendix H). A large number of DEGs related to chlorophyll synthesis (Fig. 3-D; Appendix I) and photosynthesis were upregulated (Fig. 3-E; Appendix J). The expression levels of nine genes (*CHLI1*, *CHLM*, *LHCA3*, *PRIN2*, *SG1*, *PAP6*, *NANA*, *FtsH11*, and *FLU*) were significantly higher in *Mut298* than those in WT (Appendix K), which was consistent with the transcriptome data.

3.4. Genetic analysis of mutant traits and identification of the candidate gene

Genetic analysis revealed that all *Mut298*×WT F_1 plants obtained exhibited the WT phenotype, indicating that the causal mutation in *Mut298* is recessive. In addition, 202 and 68 of *Mut298*×WT F_2 progeny exhibited the WT and mutant phenotypes, respectively, and a chi-square test confirmed a 3:1 segregation ratio, typical of a single recessive gene affecting these traits (Table 2).

The candidate region was pinpointed on chromosome 4 *via* MutMap analysis (Fig. 4-A). Utilizing a ΔSNP index greater

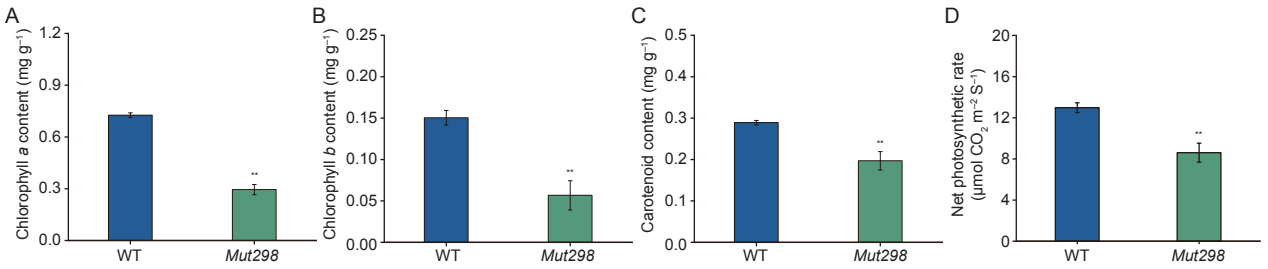


Fig. 2 Pigment content and photosynthetic parameters. A–D, levels of chlorophyll *a*, chlorophyll *b*, carotenoid, and net photosynthetic rate in WT and *Mut298*. Error bars represent standard deviation (SD; n=3). ** indicates significant differences at P<0.01 based on the Student's *t*-test.

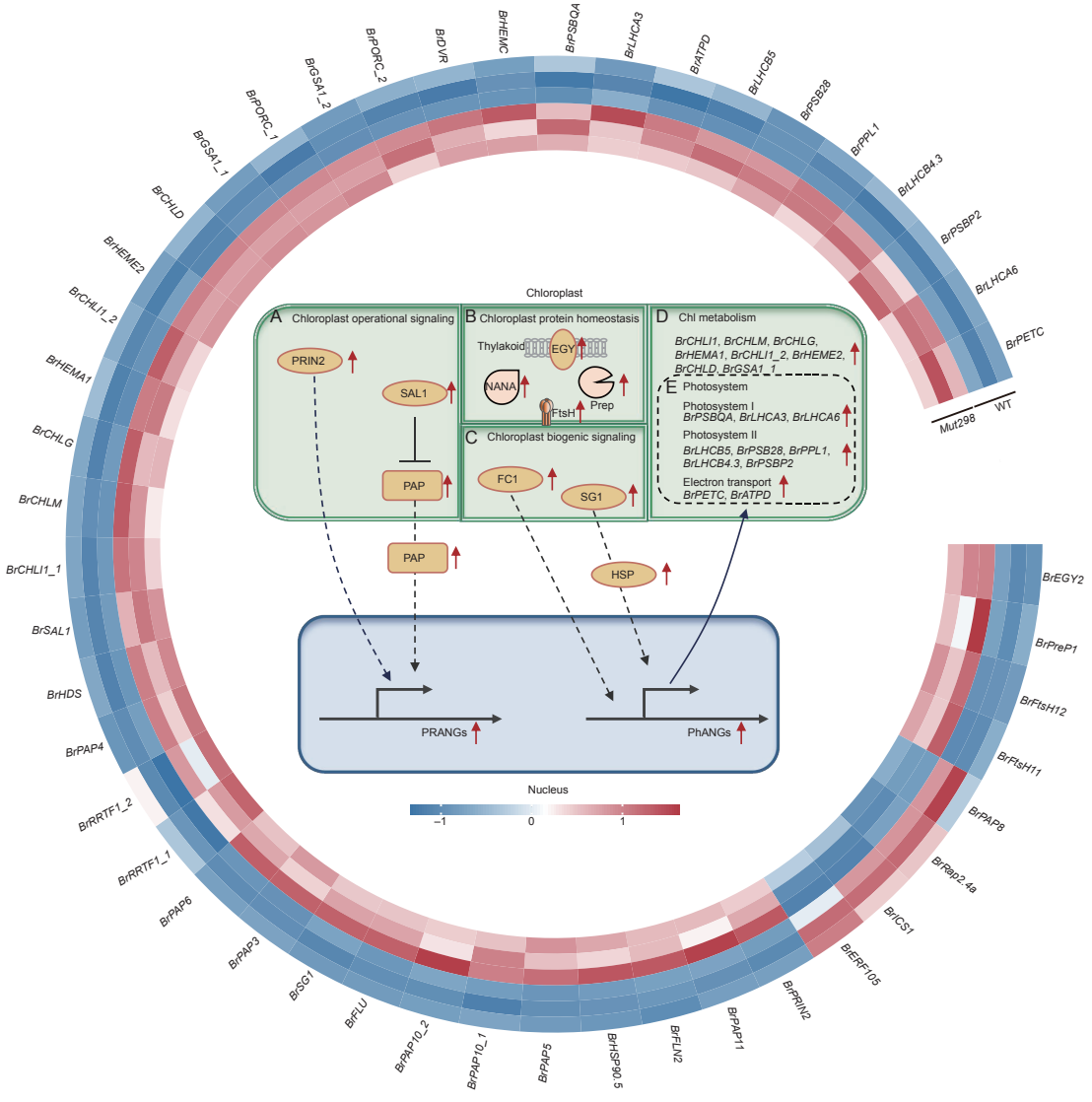


Fig. 3 The differentially expressed genes (DEGs) in chloroplast protein homeostasis and retrograde signaling. A, retrograde signaling by mature chloroplasts. B, proteolytic genes in chloroplast protein homeostasis. C, retrograde signaling by developing chloroplasts. D, chlorophyll metabolism-related genes. E, photosynthesis-related genes. Genes regulated by retrograde signals include photosynthesis-associated nuclear genes (PhANGs) and plastid redox-associated nuclear genes (PRANGs). The DEGs are visualized by heatmap. The red font represents up-regulated genes, and the blue font represents down-regulated genes. The red arrow represents up-regulated genes.

than 0.8 as the screening criterion, two non-synonymous mutation sites (*BAA04g00040* and *BAA04g02470*) were identified, each featuring a single nucleotide substitution from C to T (Table 3). PCR sequencing revealed that the genotype-phenotype correlation for *BAA04g02470* was inconsistent, leading to its preliminary exclusion from further

analysis (Appendix L). Subsequently, KASP analysis on *BAA04g00040* (*BrPRPL1*) confirmed complete concordance between genotype and phenotype in the F_2 population (Fig. 4-B–D). In the mutant line *Mut298*, a single nucleotide substitution from C to T changes glycine to arginine in the domain of *BrPRPL1* (Fig. 4-E and F).

3.5. *BrPRPL1* silencing results in leaf yellowing of Chinese cabbage

Next, we employed the Virus-Induced Gene Silencing (VIGS) technique to investigate the function of *BrPRPL1* in Chinese cabbage using the pTY vector. Plants silenced for the phytoene desaturase (*PDS*) gene displayed a bleached phenotype (Fig. 5-A), confirming the effective delivery and functionality of the VIGS system in disrupting gene expression. qRT-PCR analysis confirmed that the silencing efficiency of *BrPRPL1* in pTY-*BrPRPL1* plants was 96%, 95%, and 88%, respectively, indicating the successful silencing of *BrPRPL1* (Fig. 5-B). Silencing of the candidate gene *BrPRPL1* resulted in leaf yellowing, whereas plants transformed with the pTY empty vector control remained green (Fig. 5-A). Additionally, compared with PDS and pTY, pTY-*BrPRPL1* exhibited different colors in images generated from chlorophyll and chlorophyll fluorescence parameters (F_v/F_m, F_q'/F_m', and rETR). The imaging color of chlorophyll for PDS and pTY-*BrPRPL1* was blue, in contrast to the yellow color observed for pTY (Appendix M), indicating that chlorophyll contents in these two lines were lower than those in pTY (Appendix M). Consistent with this observation, chlorophyll *a* and chlorophyll *b* content in the pTY-*BrPRPL1* and PDS plants was indeed significantly lower by 1.2- and 9.1-fold and 1.9- and 5.3-fold, respectively, than in the pTY plants (Fig. 5-C and D). Moreover, the imaging colors of F_v/F_m and F_q'/F_m' for PDS and pTY-*BrPRPL1* were red, whereas those for pTY were yellow (Fig. 5-F and G), suggesting that the F_v/F_m and F_q'/F_m' values in PDS and pTY-*BrPRPL1* were lower than those in pTY (Fig. 5-J and K). The imaging color of the rETR for PDS and pTY-*BrPRPL1* was blue, in contrast to the red color observed for pTY (Appendix M), indicating that rETR is lower in PDS and pTY-*BrPRPL1* than in pTY (Appendix M). These results indicated that *BrPRPL1* regulates leaf color development in Chinese cabbage.

3.6. BrPRPL1 localizes to the chloroplast and affects the expression of several key ribosome-encoded proteins

The expression levels of *BrPRPL1* between *Mut298* and WT plants showed no significant difference at the seedling stage and rosette stage (Fig. 6-B). The target gene *BrPRPL1* and its mutant form *mBrPRPL1* were separately expressed in frame with a GFP tag in the pMD18-T vector in Chinese cabbage protoplasts to investigate their subcellular localization. We observed that the GFP fluorescence coincided with chlorophyll autofluorescence (Fig. 6-A), confirming the localization of *BrPRPL1* and *mBrPRPL1* within the chloroplasts.

A single nucleotide change from C to T in *BrPRPL1* significantly reduces the expression of chloroplast genome-encoded proteins. Western blot analysis revealed that the RbcL protein, encoded by the chloroplast genome and a component of Rubisco's large subunit, was expressed at significantly lower levels in *Mut298* plants compared to WT plants (Fig. 6-C). Moreover, the critical PSI proteins PsaA and PsaB were nearly absent in *Mut298* plants but expressed normally in WT plants (Fig. 6-C). These findings support a role of *BrPRPL1* in influencing the stability or expression of these key photosynthetic proteins. The expression levels of RbcL, PsaA, and PsaB in pTY-*BrPRPL1* were consistent with those in *Mut298* (Appendix N).

4. Discussion

4.1. The *BrPRPL1* mutation disrupts chloroplast ribosome translation and causes abnormal chloroplast development and leaf yellowing

In a recent study, we identified a leaf yellowing mutant of Chinese cabbage, *Mut298*, through EMS mutagenesis (Lu *et al.* 2016; Sun *et al.* 2022). The candidate gene for *Mut298* was identified as *BrPRPL1* using MutMap and KASP (Fig. 4-A–E). The silencing of *BrPRPL1* in Chinese cabbage led to significantly reduced *BrPRPL1* expression (Fig. 5-B), causing a notable yellowing phenotype (Fig. 5-A) as well as reduced chlorophyll content and chlorophyll fluorescence parameters (Fig. 5-C–L), mirroring those seen in *Mut298* plants (Fig. 1-A and B; Appendix D). These results confirm the role of *BrPRPL1* in regulating leaf yellowing in Chinese cabbage.

Rubisco is a key enzyme in photosynthesis, responsible for catalyzing the first step of carbon dioxide fixation (Cocon and Luis 2024). Here, the *BrPRPL1* mutation in Chinese cabbage disrupts ribosomal translation, markedly decreasing the levels of RbcL-the large subunit of Rubisco encoded by the chloroplast DNA (Wang *et al.* 2023)-PsaA and PsaB proteins, which are core proteins of photosystem I (PSI), in *Mut298* (Fig. 6-C), indicating severe disruption of chloroplast ribosome translation. Consistent with this result, a previous study reported that a mutation in the 50S large subunit protein of the chloroplast ribosome, encoded by the *PRPL11* gene, significantly reduces the translation rate of *RbcL*, leading to substantial reductions in the level of the PSI subunits and components of the PSII core complex (D1, D2, CP43, and CP47) as well as the α and β subunits of the ATPase complex in *Arabidopsis*, leading to a similar pale green leaf and slow growth phenotype (Pesaresi *et al.* 2001). Mutations in other chloroplast ribosomal proteins can also impair ribosome translation, thereby affecting plant growth and development. The mutation of *SVR8*, which encodes the L24 protein component of the chloroplast ribosome's large subunit in *Arabidopsis*, has been found to cause specific defects in chloroplast rRNA processing (Liu *et al.* 2013). Mutation of the plastid ribosomal protein S5 (RPS5) results in a dramatic decrease in chloroplast 16S rRNA abundance and severely impairs 16S rRNA processing, thereby affecting ribosome function and plastid translation (Zhang *et al.* 2016). These molecular defects manifest visibly as alterations in leaf color.

The *BrPRPL1* mutation identified in this research leads to chloroplast structural abnormalities (Fig. 1-C and D), which, in turn, significantly reduce chlorophyll synthesis (Fig. 2-A and B).

Table 2 Segregation ratios of F_1 and F_2 between WT and *Mut298* plants[1)]

Generation	Plants (WT phenotype)	Plants (*Mut298* phenotype)	Total plants	Segregation ratio	χ^2
F_1	10	0	10	10:0	
F_2	202	68	270	2.97:1	0.00

[1)] WT represents the wild type of Chinese cabbage.

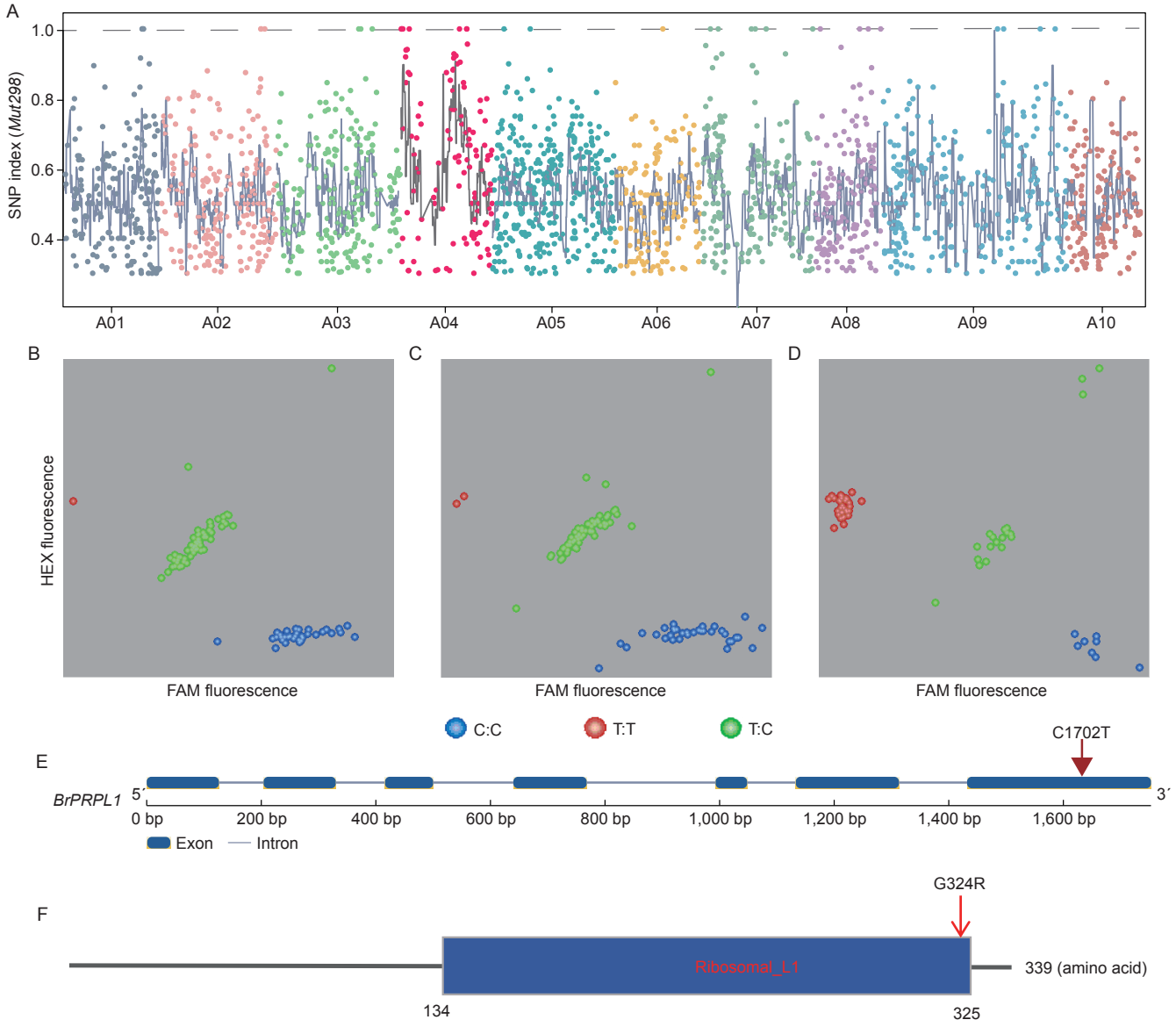


Fig. 4 *BrPRPL1* is the candidate gene. A, identification of genomic regions containing causal mutations for *Mut298* using MutMap. SNP index plots for *Mut298* span all 10 chromosomes, with individual symbols representing SNPs. The *x*-axis indicates chromosomal positions, and the mean SNP index value is depicted by a black line through sliding window analysis. SNPs on chromosome A04 represent the predicted causal mutations for *Mut298*. B–D, KASP genotyping assay for *BrPRPL1* in an F_2 population. Displays include 105 individuals on the left (F_2), 105 in the middle (F_2), and 60 on the right (3 WT, 3 *Mut298*, and 54 F_2). Blue, green, and red represent WT, heterozygous, and mutant (*Mut298*) genotypes, respectively. FAM, 6-carboxy-fluorescein; HEX, hexachlorofluorescein. E, structural diagram of *BrPRPL1* and the mutation site. The blue squares represent exons, the blue lines represent introns, and the red arrow indicates a single nucleotide substitution from C to T at 1,702 bp. F, structural diagram of BrPRPL1. The blue square represents the domain of BrPRPL1 (Ribosomal_L1). The red arrows indicate the mutated amino acid. G and R represent glycine and arginine, respectively.

In other plant species, mutations in chloroplast ribosomal proteins also alter pigment content and photosynthetic efficiency, thereby impairing plant growth and development. The *Hcf60* mutation, which disrupts small subunit protein PRPS17, significantly reduces both photosynthetic and chloroplast translation capacities, leading to light-green seedlings in maize (Schultes *et al.* 2000). In rice, the *ASL2* mutation, which encodes the chloroplast 50S ribosomal large

Table 3 Candidate genes obtained through MutMap[1)]

Gene ID	Chromosome	Structure type	Position	Wild type site	Mutant site	SNP-index
BAA04g00040	A04	Exonic (nonsynonymous)	16284	C	T	1.00
BAA04g02470	A04	Exonic (nonsynonymous)	1466890	C	T	0.92

[1)] MutMap represents genome sequencing of bulked DNA.

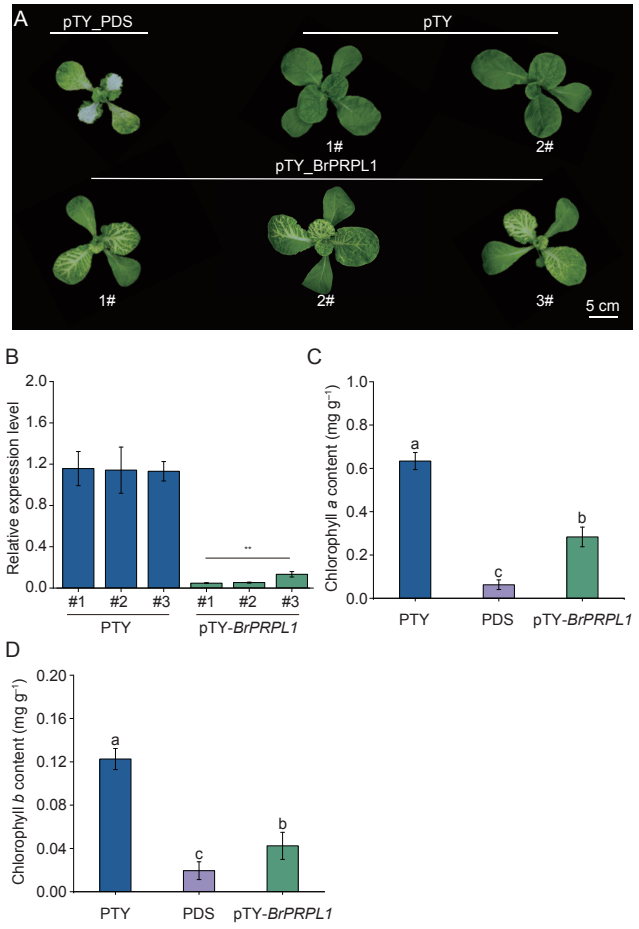


Fig. 5 Phenotypic and physiological indices of WT and *Mut298* after *BrPRPL1* silencing. A, phenotype of PDS, pTY, and pTY-*BrPRPL1* plants. B, relative expression level of *BrPRPL1* in pTY-*BrPRPL1* and pTY plants; error bars indicate SD (n=3). Asterisks (**) denote significant differences at P<0.01 based on Student's t-test. C and D, chlorophyll *a* and chlorophyll *b* content in pTY-*BrPRPL1*, pTY, and PDS plants; error bars represent SD (n=3). Letters (a, b, c) indicate significant differences as determined by Tukey's new multiple range test at P<0.05.

subunit protein L21, leads to reduced chlorophyll content and abnormal chloroplast development, producing albino seedlings (Lin *et al.* 2015). Similarly, T-DNA knockout of *prpl13* in rice significantly alters the expression levels of photosynthesis- and chloroplast development-related genes, drastically reducing chlorophyll and carotenoid content and resulting in an albino phenotype (Lee *et al.* 2019). Chlorophyll *a* and chlorophyll *b* are crucial for photosynthesis, as these molecules absorb light energy and facilitate electron transfer (Shimoda *et al.* 2012). Specifically, chlorophyll a is essential for photochemistry, while chlorophyll *b* is necessary for stabilizing the main light-harvesting chlorophyll-binding protein (Tanaka and Tanaka 2011). Consistent observations of decreased net photosynthetic efficiency and altered chlorophyll fluorescence parameters in *Mut298* (Fig. 2-D–L) underscore the pivotal role of *BrPRPL1* in maintaining chloroplast function and overall plant health. The mutation in *BrPRPL1*, a gene regulating yellow-leaf in Chinese cabbage, provides a potential target for marker-assisted breeding. By developing functional molecular markers upon identification of the mutation site sequence, early and precise selection of the yellow-leaf trait can be achieved. This marker system enhances breeding efficiency for specific objectives including backcross breeding and gene pyramiding, with particular application value for developing stress-tolerant/ornamental varieties. When this gene's editability is confirmed, the associated markers may further serve as screening tools for CRISPR-edited progenies, thereby advancing precision breeding in Chinese cabbage.

4.2. A point mutation in *BrPRPL1* does not lead to embryonic lethality in Chinese cabbage

PRPL1 is essential for embryo development and the T-DNA knockout of *PRPL1* leads to embryonic lethality in *Arabidopsis* (Romani *et al.* 2012). This lethality is linked to disruptions in essential metabolic pathways, notably the biosynthesis of fatty acids. Fatty acids are crucial components of the cell membrane and play significant roles in signal transduction and the regulation of enzyme activity. Alterations in fatty acid biosynthesis can have serious consequences during embryogenesis. The chloroplast-localized heteromeric ACCase is central to this process by converting acetyl-CoA to malonyl-CoA. The chloroplast gene *accD* in *Arabidopsis* encodes the β subunit of ACCase. Disruption of chloroplast translation affects ACCase synthesis by impacting the translation of *accD* (Bryant *et al.* 2011). Additionally, the T-DNA knockout of the gene *CAC1A*, which encodes the biotin carboxyl-carrier protein of heteromeric ACCase, results in embryonic lethality, reinforcing the critical role of proper ACCase function during early plant development in *Arabidopsis* (Li *et al.* 2011).

Chinese cabbage and *Arabidopsis* each contain one copy of the *PRPL1* gene. While *PRPL1* mutations cause embryonic lethality in *Arabidopsis*, *BrPRPL1* mutations do not lead to such severe effects in Chinese cabbage. The absence of the plastid-encoded PRPS12 leads to an albino phenotype in maize, whereas lack of PRPS12 causes embryonic lethality in *Arabidopsis* (Ostheimer *et al.* 2003; Asakura and Barkan 2006). The discrepancy may be explained by the localization of *accD* transcription and translation. In maize, *accD* is encoded in the nucleus and translated in the cytoplasm, which allows embryonic development to proceed normally despite impaired chloroplast ribosome translation (Ostheimer *et al.* 2003; Asakura and Barkan 2006; Chalupska *et al.* 2008). This may also be the reason why embryo lethality

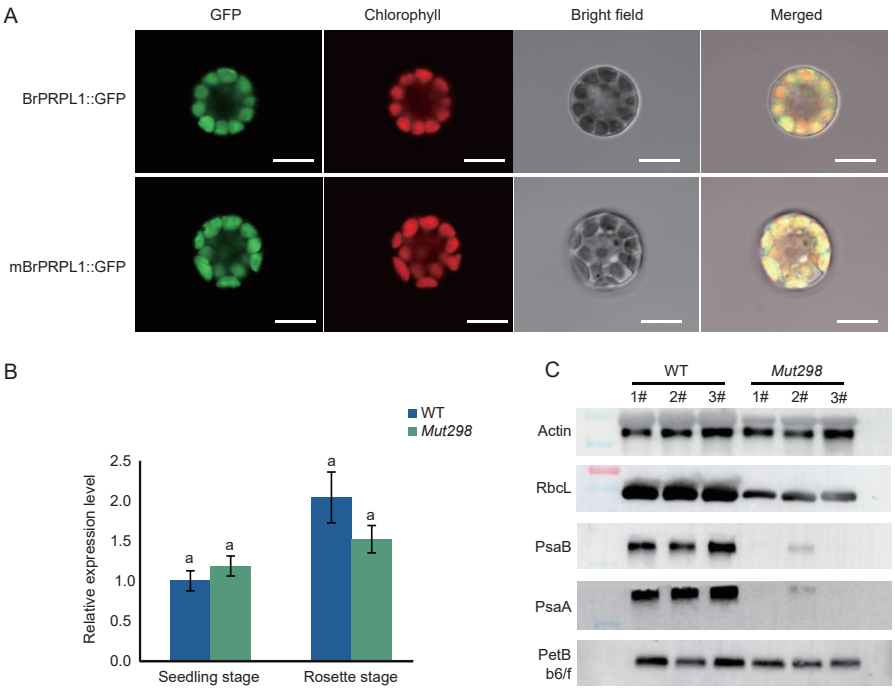


Fig. 6 Subcellular localization of BrPRPL1 and mBrPRPL1 and Western blot analysis of chloroplast-encoded proteins. A, subcellular localization of BrPRPL1 and mutant mBrPRPL1. Images display GFP (green), chlorophyll autofluorescence (red), bright field, and merged views. Scale bar=10 μm. B, relative expression levels of *BrPRPL1* at the seedling stage and rosette stage in WT and *Mut298* plants; error bars represent SD (n=3). Same letters indicate no significant differences according to Student's t-test. C, expression levels of Actin, RbcL, PsaB, PsaA, and PetB b6/f in WT and *Mut298* plants. There are three biological replicates of WT and *Mut298*.

does not occur in Chinese cabbage. The differential impacts of *PRPL1* mutations on embryonic development across species underscore the significant role of species-specific genetic and cellular contexts in determining the phenotypic outcomes of similar genetic alterations.

5. Conclusion

In this study, a golden-leaf mutant, *Mut298*, was obtained in Chinese cabbage through EMS mutagenesis. *BrPRPL1* was identified as the candidate gene regulating the yellowing leaf of Chinese cabbage. Silencing of *BrPRPL1* confirmed its involvement in regulating leaf color development of Chinese cabbage. Additionally, a single nucleotide change from C to T in *BrPRPL1* significantly reduces the expression of chloroplast genome-encoded proteins, such as RbcL, PsaA, and PsaB, and impairs chloroplast development, leading to golden yellow leaves in Chinese cabbage. To date, there have been no reports on the role of *PRPL1* in regulating leaf color development in plants. Therefore, this study enhances the understanding of the regulatory mechanisms of *PRPL1* in leaf color development and provides a theoretical foundation and genetic resources for breeding Chinese cabbage with diverse leaf colors.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use AI in the preparation and writing of this manuscript.

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