QTL Analysis for Soybean (Glycine Max L. Merr.)
Seed Storability in High-Temperature Storage Conditions

Pakanan Jiamtae
University of Miyazaki

Masatsugu Hashiguchi (mashiguchi@cc.miyazaki-u.ac.jp)
University of Miyazaki
https://orcid.org/0000-0003-0637-2780

Intouch Lelapiyamit
University of Miyazaki

Kyuya Harada
Osaka University

Takahiro Gondo
University of Miyazaki

Hidenori Tanaka
University of Miyazaki

Ryo Akashi
University of Miyazaki

Research Article

Keywords: quantitative trait locus (QTL), seed viability, seed vigor, soybean seed storability, storage condition

Posted Date: February 8th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1311025/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License
QTL analysis for soybean (*Glycine max* L. Merr.) seed storability in high-temperature storage conditions

Pakanan Jiamtak1, Masatsugu Hashiguchi2,6*, Intouch Lelapiyamit3, Kyuya Harada4, Takahiro Gondo5, Hidenori Tanaka1, Ryo Akashi1

1Interdisciplinary Graduate School of Agriculture and Engineering, University of Miyazaki, 889-2192, Miyazaki, Japan
2Faculty of Agriculture, University of Miyazaki, 889-2192, Miyazaki, Japan
3Graduate School of Agriculture, Faculty of Agriculture, University of Miyazaki, 889-2192, Miyazaki, Japan
4Department of Biotechnology, Graduate School of Engineering, Osaka University, 565-0871, Osaka, Japan
5Frontier Science Research Center, University of Miyazaki, 889-2192, Miyazaki, Japan
6Current address: Faculty of Regional Innovation, University of Miyazaki, 889-2192, Miyazaki, Japan

*Corresponding author. E-mail: mashiguchi@cc.miyazaki-u.ac.jp
Contributing authors: pakananboom8@gmail.com; mashiguchi@cc.miyazaki-u.ac.jp; intouch4510@gmail.com; haradaq@nifty.com; gondo@cc.miyazaki-u.ac.jp; htanaka@cc.miyazaki-u.ac.jp; rakashi@cc.miyazaki-u.ac.jp
ABSTRACT

Soybean (*Glycine max* L. Merr.) seeds are highly sensitive to the environmental conditions experienced in storage. The objectives of this study were to identify QTLs for soybean seed storability by evaluating seed viability and seed vigor and investigating candidate genes for these traits in detected QTL regions. These objectives will aid in developing soybean cultivars with a high capacity for storability. The seeds of 109 and 90 recombinant inbred lines (RILs) derived from a cross between Misuzudaizu and Moshidou Gong 503 in 2010 and 2019, respectively, were used to evaluate seed viability by a germination test and seed vigor by an accelerated aging test, after storage under two temperature conditions (25 °C and 35 °C) for six months. Seed viability and seed vigor of Moshidou Gong 503 were higher than those of Misuzudaizu in both temperature conditions. The average seed viability and seed vigor of RILs decreased when stored at the higher temperature. A total of five QTLs were found for the two traits, seed viability and seed vigor, located in chromosomes A2, C2, and D1b. The Misuzudaizu alleles decreased seed viability and seed vigor at all detected QTLs. Most QTLs in this study were found near loci controlling seed viability, maturity, germination, seed hardiness, and seed surface micromorphology, indicating that seed storability is related to these traits. In addition, two new QTLs were found that are associated with seed storability.

Keywords: quantitative trait locus (QTL), seed viability, seed vigor, soybean seed storability, storage condition
INTRODUCTION

Seed storability is of paramount importance in agricultural production. Short longevity due to loss in seed viability and vigor during storage negatively impacts seedling development and crop productivity (Han et al. 2014; Börner et al. 2018). Reduced seed viability and seed vigor due to seed deterioration is influenced by high temperature and humidity in the storage environment that affects biochemical processes in seeds, such as increases in hydrolytic enzyme activity, enhanced respiration, and lipid peroxidation leading to increased levels of free fatty acids (Copeland and McDonald 2001).

Lipid peroxidation (Wang et al. 2018) and protein damage (Davies 2005) always occur in oilseed crops during high-temperature storage. In humid tropical and sub-tropical climates, including Southeast Asia, where temperature and relative humidity are high, the rapid loss in seed germination ability during storage is a major problem in soybean production (Nkang et al. 1996).

Soybean is the most important legume crop globally because the seeds contain large amounts of storage components, including proteins and lipids, used for food, feed and many industrial materials. Seed proteins and lipids are susceptible to high temperatures and elevated humidity in storage. In unconditioned storage environments, soybean seed deterioration occurs rapidly (TeKrony et al. 1993). Lengthy storage of soybeans causes reduced seed longevity, lower levels of germination, and impaired seedling establishment due to the utilization of several molecules during seed respiration. Thus, developing cultivars with significant resistance to high-temperature storage is necessary to improve seed viability and vigor during storage. Nevertheless, understanding the genetic bases for seed storability is insufficient; we must also develop genetic material with resistance to storage conditions. Genetic analyses should be conducted to identify soybean genotypes that are resistant to storage conditions and to develop genetic markers for marker-assisted selection (MAS).

Several genetic analyses of seed storability have been reported in Arabidopsis (Clerkx et al. 2004), rice (Sasaki et al. 2005; Xue et al. 2008; Wang et al. 2010 Li et al. 2012; Miura et al. 2002), rye seed (Chwedorzewska et al. 2002), safflower (Vijay et al. 2009) and soybean (Green and Pinnell 1968; Lanyon 1970; Kueneman 1983; Singh and Ram 1986; Verma and Ram 1987; Cho and Scott 2000; Singh et al. 2008). Verma and Ram (1987) found that two to four genes presumably control seed longevity in soybean. Polymorphisms in RAPD profiles of aged soybean seeds were found and four SSR markers were associated with seed coat permeability and electrolyte leaching in soybean (Singh et al. 2008). Four SSR markers related to seed longevity in an F<sub>2:3</sub> soybean population derived from a cross between good...
and poor storage genotypes have been reported (Singh et al. 2008a). Vijay et al. (2009) clustered the genetic variation of safflower and soybean into three different seed age groups, including un-aged, naturally aged, and age-accelerated seeds by RAPD, AFLP, and SSR markers. RAPD markers clustered naturally aged and age-accelerated seeds types in soybean and safflower, whereas the control and naturally aged seed were clustered by SSR and AFLP markers (Vijay et al. 2009).

Quantitative Trait Loci (QTL) analysis is effective because seed storability is a quantitative trait controlled by several genes. Several QTL analyses of seed storability have been reported in Arabidopsis (Bentsink et al. 2000; Clerkx et al. 2004), rice (Sasaki et al., 2005; Xue et al. 2008; Wang et al. 2010; Li et al. 2012; Miura et al. 2002), barley (Nagel et al. 2016), maize (Han et al. 2014) and oilseed rape (Nagel et al. 2011). In soybean, QTLs associated with seed storability remain to be identified and characterized, and there are no studies of QTL analysis for seed storability based on seed vigor and under high temperature and long term storage condition. Although QTLs controlling seed storability have been reported, genes responsible for seed storability have not yet been identified. Dargahi et al. (2014) reported that there are three QTLs on three linkage groups that are associated with seed storability. However, this report found the QTLs in seeds under ambient condition and accelerated aging.

In this study, a RIL population derived from a cross between Misuzudaizu and Moshidou Gong 503 was stored under two different temperatures to evaluate seed viability and seed vigor. The objectives of this study were to identify QTLs for seed storability at the two different temperatures and analyze the responsible genes by detecting QTL regions.

MATERIALS AND METHODS

Plant materials

Recombinant inbred lines (RILs) derived from a cross between Misuzudaizu and Moshidou gong 503 were obtained from the National BioResource Project (NBRP) for Lotus and Glycine, University of Miyazaki. Misuzudaizu is a yellow soybean seed cultivar developed at the Nagano Prefectural Agricultural Experiment Station, Japan and Moshidou Gong 503 is a brown soybean seed line originating from Jilin province, China. In 2010 and 2019, 109 and 90 RILs, respectively, were used in this study.

Seed storage conditions
Seeds were stored in paper bags (19.5 cm × 11.9 cm) at 25±1 °C or 35±1 °C at 40–57% relative humidity for six months.

**Seed viability**

Seed viability was evaluated by the between-paper germination test (Rao et al. 2006). Three replications of 30 seeds from the RILs were placed between moistened double-folded paper towels (size 40 × 33 cm). After being scarified to break seed dormancy, the seeds were moved to Plant Boxes for Plant Culture (125mL, size 75 × 75 × 100 mm VWR International, USA) and placed into incubators at 25 °C for eight days (ISTA 2011). At the end of the treatment, the number of normal seedlings was counted. The germination percentage was calculated as the number of normal seedlings/number of all seeds × 100.

**Seed vigor**

The accelerated aging (AA) test (ISTA 2011) was used to evaluate seed vigor. Seeds were treated at 41 ± 1 °C and 100% relative humidity for 72 h. Subsequently, the between-paper germination test was conducted. After eight days, the number of normal seedlings was counted. Seeds with higher germination percentages indicated greater seed vigor.

**QTL analysis**

The markers used in this study were a total of 1,131 simple sequence repeat (SSR) markers from the Glycine max / G. soja database at LegumeBase: (https://www.legumebase.brc.miyazakiu.ac.jp/glycine/rilChromosome/rilChromosomeList.jsp) where genotypes and physical maps of all RIL populations are also available. The map had a distance of 3,240.72 cM among 20 linkage groups (LGs), and the average genetic distance between two neighboring marker loci was 2.87 cM. The presence of QTLs was calculated by composite interval mapping using R/qtl software (Broman et al. 2003). The logarithm of odd (LOD) value significance threshold was determined by a permutation test module (1000 replications).

**Data analysis**

The effects of genotype and storage temperature on seed viability and seed vigor were indicated by seed germination and AA tests, based on an analysis of variance (ANOVA), calculated by R software. All treatments were considered as effects, whereas interactions with replication were treated as random effects. Means and interactions were compared by Duncan’s test with least-square means comparisons.
RESULTS

Seed viability

The initial germination percentages of Misuzudaizu in 2010 and 2019 were 80% and 60%, respectively, whereas those of Moshidou Gong 503 were 80% and 100%, respectively. In contrast, the initial germination percentage of the RILs in 2010 ranged from 0% to 100% with an average of 59.75%, and those of the RILs in 2019 ranged from 0% to 90% with an average of 26.33% (Table 1). The germination percentages of Misuzudaizu 503 in 2010 and 2019 after storage at 25 °C for six months were 10% and 60%, respectively, and those of Moshidou Gong 503 were 45% and 80%, respectively. The germination percentage of the RILs stored at 25 °C for six months in 2010 ranged from 0% to 73% with an average of 29.57%, and those of the RILs in 2019 ranged from 0% to 100% with an average of 34.33% (Table 1). Storage at 35 °C for six months resulted in a germination percentage for Misuzudaizu in 2010 and 2019 of 0% and 40%, respectively and those of Moshidou Gong 503 were 20%, and 60%, respectively. The 2010 RILs had germination percentages ranging from 0% to 60% with an average of 7.19% (Figure 1.), and those of the 2019 RILs ranged from 0% to 100% with an average of 23.67% (Table 1).

Seed vigor

After conducting the accelerated aging test, the germination percentages of Misuzudaizu in 2010 and 2019 were 10% and 20%, respectively, and those of Moshidou Gong 503 were 40%, and 80%, respectively. Germination percentages of the 2010 RILs ranged from 0% to 80% with an average of 15.63%, and those of the 2019 RILs ranged from 0% to 80% with an average of 12.56% (Table 1, Figure 1). The germination percentages of Misuzudaizu stored at 25 °C for 6 months in 2010 and 2019 were 0% and 40%, respectively, whereas those of Moshidou Gong 503 were 20%, and 80%, respectively. In contrast, the germination percentages of the 2010 RILs ranged from 0% to 60% with an average of 4.59%, and those of the 2019 RILs ranged from 0% to 80% with an average of 15.89% (Table 1, Figure 1.). The germination percentages of Misuzudaizu 503 in 2010 and 2019 stored at 35 °C for 6 months were 0% and 20%, respectively, whereas those of Moshidou Gong 503 were 10% and 60%, respectively. RILs stored at 35 °C for 6 months in 2010 ranged from 0% to 60% with an average of 3.85%, and similarly stored RILs in 2019 ranged from 0% to 90% with an average of 11.54% (Table 1).

Effect of line and storage temperature on seed viability and seed vigor
An analysis of variance for seed viability and seed vigor after storage at each condition is shown in Table 2. Significant two-way interactions among lines X storage temperature ($P>0.0001$) were observed for seed viability and seed vigor, except for seed viability in 2019.

**QTL analysis**

A total of five QTLs were identified for two traits, seed viability and seed vigor (Table 3). For seed viability after storage at 35 °C for six months, a QTL ($qSG-A2$) with an LOD value of 4.03 and a phenotypic variance of 6.84% was detected on Chromosome A2. In seeds tested for seed vigor in the untreated condition in 2010, a QTL ($qSV-C2.1$) was detected on Chromosome C2 with an LOD value of 3.64 and a phenotypic variance of 16.6%. For seed vigor at 35 °C for six months, a QTL ($qSV-C2.2$) was detected on Chromosome C2 in 2010 with an LOD value of 2.95 and a phenotypic variance of 4.34%. For seed vigor in the untreated condition in 2019, a QTL ($qSV-C2.3$) was detected on Chromosome C2 with an LOD value of 4.13 and a phenotypic variance of 13.1%. For seed vigor at 25 °C for six months, a QTL ($qSV-D1b$) was detected on Chromosome D1b with an LOD value of 5.02 and a phenotypic variance of 16.6% (Figure 2).

**DISCUSSION**

Soybean is categorized in the poor storability group of crop plants (Justice and Bass 1978). The environmental conditions for storage are significant factors influencing seed viability and vigor. This study used soybean recombinant inbred lines derived from a cross between Misuzudaizu (yellow) and Moshidou Gong 503 (brown) harvested in 2010 and 2019 and used to evaluate seed viability and vigor and to identify QTLs controlling seed storability. In comparing the germination percentage in the parental lines, Moshidou Gong 503 had a higher germination percentage in high temperature and long-term storage than Misuzudaizu. After conducting the AA test, the germination percentage of Misuzudaizu, Moshidou Gong and the RILs decreased (Table 1). In particular, the germination percentage of Misuzudaizu was as low as 10% in untreated seed, whereas AA treated seeds failed to germinate in 2010 (Table 1).

Genetic factors play a role in soybean seed storability (Shelar et al. 2008). Seed storability is a complex quantitative trait controlled by multiple genes and is easily influenced by the environment. Genetic loci associated with seed storability should be identified to develop cultivars resistant to
storability issues and to characterize ways of controlling seed storability. This study found five QTLs associated with seed storability, four QTLs for seed vigor and one QTL for seed viability. A Misuzudaizu allele decreased seed viability at $qSG-A2$ and showed similar effects at the QTLs $qSV-C2.1$, $qSV-C2.2$, $qSV-C2.3$ and $qSV-D1b.1$. The QTLs $qSV-C2.1$, $qSV-C2.2$ and $qSV-C2.3$ were located and closely placed on the same chromosome C2. Only $qSV-D1b.1$ was located elsewhere on chromosome D1b. Watanabe et al. (2004) found sixty-six QTLs associated with three reproductive development traits and four seed quality traits as well as Otobe et al. (2015) cloud detected five QTLs associated with micromorphology on the seed coat surface in RILs population derived from a cross between Misuzudaizu and Moshidou Gong 503 using the total of 360 markers. However, the total of 1,131 markers were used in this study and five QTLs associated with seed storability were detected. In comparing our QTL results with QTLs for seed quality, we found that the $qSV-C2.2$ and $qSV-C2.3$ QTLs are new because they have not been associated with any other QTLs in previous reports. The $qSG-A2$ QTL was located close to QTLs for maturity ($HAV4$), seed viability ($VIS4$) (Watanabe et al. 2004), and seed surface micromorphology (Otobe et al. 2015). The mapped location of $qSV-C2.1$ was close to QTLs for germination rate ($GRS1$) and seed hardness ($RAS1$) (Watanabe et al. 2004). The $qSV-D1b.1$ QTL was located close to QTLs for seed hardness ($RAS2$) (Watanabe et al. 2004) and a seed surface trait ($qSR3$) (Otobe et al. 2015). For QTL associated with seed storability, Daragahi et al. (2004) used the total of 128 SSR makers constructed 38 linkage groups and identified three QTLs on three linkage groups (C1, F and L) associated with seed storability in soybean under ambient condition (28 ± 2°C) for 5 months and accelerated aging (42 ± 1°C) for 72 h, and no stable QTL were found in different years. However, this study used 1,131 SSR markers and found five QTLs associated with seed storability on three linkage groups (A2, C2 and D1b) from 20 linkage groups, three QTLs located on same linkage group (C2) and the QTLs for seed vigor of untreated seeds in both 2010 and 2019 were stable QTLs. Moreover, QTLs for seeds viability under high temperature condition (35°C for 6 months) were found in this study.

Our study identifies for the first time two new QTLs for seed vigor that were found in treated seeds stored at 35 °C for six months in 2010 and untreated seeds in 2019. Seed vigor analyzed by the accelerated aging test (AA Test) imitates stressful conditions for soybean seeds. Seeds with high vigor can tolerate stressful conditions during the AA Test. Therefore, evaluating seed vigor by the AA Test can detect changes in vigor more sensitively than the standard germination test. For seed viability, Watanabe et al. (2004) found five QTLs associated with seed viability; however, only $qSG-A2$ was found
in our study since seeds were stored long term at a high temperature. Moreover, qSG-A2 was found to be located closely positioned on the same chromosome as VIS4, a QTL initially reported by Watanabe et al. (2004).

Seed longevity is thought to be progressively acquired during maturation and reaches its maximum during the seed filling phase or a later maturation phase (Zanakis et al. 1994; Gillen et al. 2012; Marcos-Filho J. 2016; Lima et al. 2017). The finding that the qSG-A2 QTL was located close to the HAV4 QTL may indicate a relationship between seed longevity and seed maturation.

Pigmented seeds have higher germination rates and vigor than unpigmented seed coats and exhibit higher resistance to deterioration during storage (Singh and Ram 1986; Liu et al. 2017). Most hard seed characteristics in dark-colored soybeans are associated with permeability and protection against abiotic and biotic stresses and function to protect seeds from deterioration and to maintain seed vigor during long storage periods. There are multiple cell layers in the seed coats of dark seeds filled with phenolic compounds that function as antioxidants (Liu et al. 2017) and may act to reduce metabolic activity. Moshidou Gong 503 is a brown accession with a high degree of seed storability due to increased seed hardness and a smooth seed surface (Otobe et al. 2015). Smooth seed surfaces are derived from waxy materials that protect the seed from the environment and confer seed impermeability. Most yellow soybean seeds lose germination ability during storage and aging due to their thin and weak seed coats with wide pores. Although seed dormancy was broken by scarification in our study, some seeds were not viable and could not germinate. Soybean seeds stored long term in high temperature conditions had low seed viability and seed vigor. During storage, the influence of fatty acid metabolism continues to be important. During longer storage periods, the concentrations of fatty acid glucosides and aglycon increase, whereas the levels of acetyl glucoside and malonyl glucoside decreased after three years (Liu et al. 2017). Thus, deterioration at the biochemical, physiological and molecular levels may occur during storage, especially lipid peroxidation and membrane lipid hydrolysis.

In conclusion, seed storability is related to several seed quality traits. Most QTLs controlling seed storability are related to other QTLs for seed quality. The two new QTLs found in this study will provide useful information for identifying genes responsible for seed storability and for developing soybean cultivars with higher degrees of storability in the future. Although QTLs that regulate seed storage have been discovered, seed storability depends on the biochemical and physiological processes occurring in stored seeds. Changes in seed components that occur during seed storage are dynamic, and
the relationship between the degrading enzymes and other factors involved in these changes should be
analyzed in the future.

Acknowledgment

This work was supported by the National BioResource Project (NBRP) of the Japan Agency for Medical
Research and Development (AMED).

Author contributions

For conceptualization was design by MH, KH and PJ. Material preparation and data collection were
performed by PJ. Data analysis was performed by PJ and IL. The first draft of the manuscript was written
by PJ and MH and all author commented on previous versions of the manuscript. All authors read and
approved the final manuscript.

Ethics declarations

Conflicts of interest The author declare that there is no conflict of interest.

Ethics approval This research did not involve research with human participants and/or animals.

Consent to participate All author have reviewed the manuscript and approved their participation.

Consent for publication All author have reviewed the manuscript and approved its submission.

Funding

This work was support by the National BioResource Project (NBRP) of the Japan Agency for
Medical Research and Development (AMED).

Data availability

The dataset in this study is available on the on the Glycine max / G. soja database in LegumeBase:
(https://www.legumebase.brc.miyazakiu.ac.jp/glycine/rilChromosome/rilChromosomeList.jsp).
REFERENCE

Bentsink L, Alonso-Blanco C, Vreugdenhil D, Tesnier K, Groot SPC, Koornneef M (2000) Genetic analysis of seed-soluble oligosaccharides in relation to seed storability of Arabidopsis. Plant Physiol 124:1595–1604. https://doi.org/10.1104/pp.124.4.1595

Börner A, Nagel M, Agacka-Mołdoch M, Gierke PU, Oberforster M, Albrecht T, Mohler V (2018) QTL analysis of falling number and seed longevity in wheat (Triticum aestivum L.). J Appl Genet 59(1):35–42. https://doi.org/10.1007/s13353-017-0422-5

Chwedorzewska KJ, Bednarek PT, Puchalski J (2002) AFLP profiling long term stored and regenerated rye gene bank sample. Cell Mol Biol Lett 7: 569-576. PMID: 12378250.

Clerkx EJM, Vries BD, Ruys G J, Groot SPC, Koornneef M (2004) Genetic differences in seed longevity of various Arabidopsis mutants. Physiol Plant 121:448–461. https://doi.org/10.1111/j.0031-9317.2004.00339.x

Copeland LC, McDonald MB (2001) Principles of seed science and technology. 4th edition, USA.

Dargahi H, Tanya P, Srinives P (2014) Mapping of the genomic regions controlling seed storability in soybean (Glycine max L.). J Genet 93:365–370. https://doi.org/10.1007/s12041-014-0381-0

Davies MJ (2005) The oxidative environment and protein damage. Biochimica et Biophysica Acta 1703: 93-109. https://doi.org/10.1016/j.bbabap.2004.08.007

Green DE, Pinnell EL (1968) Inheritance of soybean seed quality I: Heritability of laboratory germination and field emergence. Crop Sci 8:5-11. https://doi.org/10.2135/cropsci1968.0011183X000800010003x

Gillen AM, Smith JR, Mengistu A, Bellaloui N (2012) Effects of maturity and Phomopsis longicolla on germination and vigor of soybean seed of near-isogenic lines. Crop Sci 52 :2757–2766. https://doi.org/10.2135/cropsci2011.10.0566

Han Z, Ku L, Zhang Z, Zhang J, Guo S, Liu H, Zhao R, Ren Z, Zhang L, Su H, Dong L, Chen Y (2014) QTLs for seed vigor-related traits identified in maize seeds germinated under artificial aging conditions. PLoS One 9(3): e92535. https://doi.org/10.1371/journal.pone.0092535

International Seed Testing Association [ISTA] (2011) Seed Vigour Testing. International Rule for Seed Testing, Zurich, Switzerland.
Justice OL, Bass LN (1978) Principles and practices of seed storage. Agriculture Handbook 506. Science and Education Administration, USDA, Washington D.C., USA

Li LF, Lin QY, Liu SY, Liu X, Wang WY, Hang NT, Liu F, Zhao ZG, Jiang L, Wan J (2012) Identification of quantitative trait loci for seed storability in rice (Oryza sativa L.). Plant Breeding 131:739-743. https://doi.org/10.1111/j.1439-0523.2012.02007.x

Li LF, Lin QY, Liu SY, Liu X, Wang WY, Hang NT, Liu F, Zhao ZG, Jiang L, Wan J (2012) Identification of quantitative trait loci for seed storability in rice (Oryza sativa L.). Plant Breeding 131:739-743. https://doi.org/10.1111/j.1439-0523.2012.02007.x

Lima JJP, Buitink J, Lalanne D, Rossi RF, Pelletier S, Silva EAA et al (2017) Molecular characterization of the acquisition of longevity during seed maturation in soybean. PLoS One 12:1–25. https://doi.org/10.1371/journal.pone.0180282

Liu J, Qin WT, Wu HJ, Yang CQ, Deng JC, Iqbal N, Liu WG, Du JB, Shu K (2017) Metabolism variation and better storability of dark-versus light-colored soybean (Glycine Max L. Merr.) seeds. Food chemistry 233:104-113. https://doi.org/10.1016/j.foodchem.2016.12.036

Marcos-Filho J (2016) Seed physiology of cultivated plants. 2nd Edition, ABRATES, Londrina

Miura K, Lin SH, Yano M, Nagamine T (2002) Mapping quantitative trait loci controlling seed longevity in rice (Oryza sativa L.) Theor Appl Genet 104:981-986. https://doi.org/10.1007/s00122-002-0872-x

Nagel M, Rosenhauer M, Willner E, Snowdon RJ, Friedt W, Börner A (2011) Seed longevity in oilseed rape (Brassica napus L.) genetic variation and QTL mapping. Plant Genet Resour 9:260–263. https://doi.org/10.1017/S1479262111000372

Nagel M, Kodde J, Pistrick S, Mascher M, Börner A, Groot SP (2016) Barley seed aging: genetics behind the dry elevated pressure of oxygen aging and moist controlled deterioration. Front Plant Sci 7:388. https://doi.org/10.3389/fpls.2016.00388

Nkang A, Umlo EO (1996) Six month storability of five soybean cultivars as influenced by stage of harvest, storage temperature and relative humidity. Seed Sci Technol 25:93-99

Otobe K, Watanabe S, Harada K (2015) Analysis of QTLs for the micromorphology on the seed coat surface of soybean using recombinant inbred lines. Seed Sci Res 25:409–415. https://doi.org/10.1017/S0960258515000318

R Development Core Team (2013) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria https://www.R-project.org/. Accessed 20 June 2021
Rao NK, Hanson J, Dulloo ME, Ghosh K, Nowell D, Larinde M (2006) Between-paper method in the “Manual of seed handling in genebanks. Handbooks for Genebanks No. 8. Bioversity” International, Rome, Italy. pp 61-62

Sasaki K, Fukuta K, Sato T (2005) Mapping of quantitative trait loci controlling seed longevity of rice (Oryza sativa L.) after various periods of seed storage. Plant Breeding 124:361-366. https://doi.org/10.1007/s00122-002-0872-x

Shelar VR, Shaikh RS, Nikam AS (2008) Soybean seed quality during storage: a review. Agriculture Review 29(2):125-131.

Singh RK, Ram HH (1986) Inheritance study of soybean seed storability using an accelerated ageing test. Field Crop Research 13(1):89-98. https://doi.org/10.1016/0378-4290(86)90013-4

Singh RK, Raipurai RK, Bhatia VS, Rani A, Pushpendra T, Husain SM, Satyavathi CT, Chauhan GS, Mohapatra T (2008) Identification of SSR markers associated with seed coat permeability and electrolyte leaching in soybean. Physiol Mol Biol Plants 14:173-177. https://doi.org/10.1007/s12298-008-0016-0

Singh RK, Raipurai RK, Bhatia VS, Rani A, Pushpendra T, Husain SM, Satyavathi CT, Chauhan GS, Mohapatra T (2008) SSR markers associated with seed longevity in soybean. Seed sci and Tech 36:162-167. https://doi.org/10.15258/sst.2008.36.1.17

TeKrony DM, Nelson C, Egli DB, White GM (1993) Predicting soybean seed germination during warehouse storage. Seed Sci Technol 21:127-137.

Verma VD, Ram HH (1987) Genetics of seed longevity in soybean. Crop Improvement 14: 42-46

Vijay D, Dadlani M, Kumar PA, Panguluri SK (2009) Molecular marker analysis of differentially age seed of soybean and safflower. Plant Mol Report 27: 282-291. https://doi.org/10.1007/s11105-008-0085-9

Wang Z, Wang J, Bao J, Wang F, Zhang H (2010) Quantitative trait loci analysis for rice seed vigor during the germination stage. J Zhejiang Univ Sci B 11:958-964. https://doi.org/10.1631/jzus.B1000238

Wang T, Hou L, Jian H, Di F, Li J, Liu L (2018) Combined QTL mapping, physiological and transcriptomic analyses to identify candidate genes involved in Brassica napus seed aging. Mol Genet Genomics 293:1421-1435. https://doi.org/10.1007/s00438-018-1468-8
Watanabe S, Tajuddin T, Yamanaka N, Hayashi M, Harada K (2004) Analysis of QTLs for reproductive development and seed quality traits in soybean using recombinant inbred lines. Breed Sci 54:399–407. https://doi.org/10.1270/jsbbs.54.399

Xue Y, Zhang S, Yano Q, Peng R, Xiong A, Li X, Zhu W, Zhu Y, Zha D (2008) Identification of quantitative trait loci for seed storability in rice (Oryza sativa L.). Euphytica 164:739-744. https://doi.org/10.1007/s10681-008-9696-3

Zanakis GN, Ellis RH, Summerfield RJ (1994) Seed quality in relation to seed development and maturation in 3 genotypes of soyabean (Glycine max). Expl Agric 30:139–156. https://doi.org/10.1017/S0014479700024091
Fig 1. Frequency distribution of seed viability and seed vigor in each storage condition for RIL seeds in 2010 and 2019. (A) seed viability of 35°C/6 months storage in 2010, (B) seed vigor of untreated seed in 2010, (C) seed vigor of 35°C/6 months storage in 2010, (D) seed vigor of untreated seed in 2019 and (E) seed vigor of 25°C/6 months storage in 2019. ▼: Misuzudaizu, ▽: Moshidou Gong 503

Fig 2. Quantitative trait locus (QTL) analysis, showing composite interval mapping for seed viability ($qSG$) and seed vigor ($qSV$) in 2010 (-----) and 2019 (—), Black arrowheads indicate QTL for seed viability and seed vigor.
Table 1 Analysis of seed viability and seed vigor in the parental and RIL populations

| Year | Storage condition | Accelerated aging (AA)* | Germination rate (%) | Parents | RIL population |
|------|------------------|-------------------------|----------------------|---------|----------------|
|      |                  |                         |                      | Misuzudaizu | Moshidou Gong 503 | Range | Average |
| 2010 | Untreated        | -                       | 80                   | 80             | 0-100          | 59.75 |
|      |                  | +                       | 10                   | 40             | 0-80           | 15.63 |
|      | 25 °C            | -                       | 10                   | 45             | 0-73           | 29.57 |
|      |                  | +                       | 0                    | 20             | 0-60           | 4.59  |
|      | 35 °C            | -                       | 0                    | 20             | 0-60           | 7.19  |
|      |                  | +                       | 0                    | 10             | 0-60           | 3.85  |
| 2019 | Untreated        | -                       | 60                   | 100            | 0-90           | 26.33 |
|      |                  | +                       | 20                   | 80             | 0-80           | 12.56 |
|      | 25 °C            | -                       | 60                   | 80             | 0-100          | 34.33 |
|      |                  | +                       | 40                   | 80             | 0-80           | 15.89 |
|      | 35 °C            | -                       | 40                   | 60             | 0-100          | 23.67 |
|      |                  | +                       | 20                   | 60             | 0-90           | 11.54 |

* Seeds were germinated after with (+) and without (-) an accelerated aging (AA) treatment.
**Table 2** Analysis of variance for seed viability and seed vigor of 109 RILs in 2010 and 109 RILs in 2019 after storage at each condition.

| Effect      | Seed viability | | | | Seed vigor | | | |
|-------------|---------------|---|---|---|---------------|---|---|---|
|             | 2010 df F-value P > F | 2019 df F-value P > F | 2010 df F-value P > F | 2019 df F-value P > F |
| Line (L)    | 108 4.30 <0.0001 | 89 3.34 <0.0001 | 108 15.20 <0.0001 | 89 7.04 <0.0001 |
| Temperature (T) | 2 725.27 <0.0001 | 2 5.14 0.0067 | 2 172.81 <0.0001 | 2 5.91 0.0032 |
| L × T       | 216 2.82 <0.0001 | 178 1.07 0.3185 | 216 5.39 <0.0001 | 178 2.27 <0.0001 |
| Year | Traits                  | Condition | QTL     | LG  | Marker               | Position (cM) | LOD  | PVE  | $R^2$ (%) |
|------|-------------------------|-----------|---------|-----|----------------------|---------------|------|------|------------|
| 2010 | Seed viability          | 35°C/6 M  | $qSG-A2$ | A2  | GMES1620             | 53            | 4.03 | -5.13| 6.84       |
|      | Seed vigor              | Untreated | $qSV-C2.1$ | C2  | MOJI.C               | 119           | 3.64 | -8.31| 16.6       |
|      |                         | 35°C/6 M  | $qSV-C2.2$ | C2  | E8M18Mo1000A         | 121.9         | 2.95 | -4.07| 4.34       |
| 2019 | Seed vigor              | Untreated | $qSV-C2.3$ | C2  | Sat_238              | 128           | 4.13 | -9.79| 13.1       |
|      |                         | 25°C/6 M  | $qSV-D1b$ | D1b | GMS05538             | 127           | 5.02 | -11.4| 16.6       |
