

Registration of 'Thunder CL' Wheat

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ABSTRACT

'Thunder CL' (Reg. No. CV-1031, PI 655528) hard white winter wheat (*Triticum aestivum* L.) was developed by the Colorado Agricultural Experiment Station and released in August 2008 through a marketing agreement with the Colorado Wheat Research Foundation. In addition to researchers at Colorado State University (CSU), USDA-ARS researchers at Manhattan, KS, St. Paul, MN, and Pullman, WA, participated in the development of Thunder CL. Thunder CL was selected from the cross KS01-5539/CO99W165 made in 2000 at Fort Collins, CO. KS01-5539 is an unreleased experimental line from Kansas State University with the pedigree FS2/KS97HW150//KS97HW349, and CO99W165 is an unreleased experimental line from CSU with the pedigree KS92WGRC25/'Halt'. Thunder CL was derived from a population advanced from the F_2 to F_4 by single-seed descent. Thunder CL was selected as an $F_{4.5}$ line in September 2003 and assigned experimental line number CO03W239. Thunder CL was released because of its superior grain yield under nonirrigated and irrigated production conditions in eastern Colorado, it carries the *Als1* gene for tolerance to imazamox herbicide, it is moderately resistant to wheat streak mosaic virus, stripe rust (*Puccinia striiformis* f. sp. tritici), and stem rust (*P. graminis* f. sp. tritici), and it has superior milling and bread baking quality.

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Abbreviations: CSU, Colorado State University; PPO, polyphenol oxidase; SRPN, Southern Regional Performance Nursery.

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August 2008 through a marketing agreement with the Colorado Wheat Research Foundation. In addition to researchers at Colorado State University (CSU), USDA-ARS researchers at Manhattan, KS, St. Paul, MN, and Pullman, WA, participated in the development of Thunder CL. Thunder CL was selected from the single cross KS01-5539/CO99W165 made in 2000 at Fort Collins, CO. KS01-5539 is an unreleased experimental line from Kansas State University with the pedigree FS2/KS97HW150//KS97HW349. The wheat germplasm line FS2 was developed by BASF Corporation (formerly American Cyanamid) using sodium azide-induced mutagenesis of the French wheat cultivar Fidel to obtain tolerance to the imidazolinone class of herbicides (Newhouse et al., 1992). CO99W165 is an unreleased experimental line from CSU with the pedigree KS92WGRC25 (PI 574490)/'Halt' (Martin and Harvey, 1995; Quick et al., 1996).

Thunder CL was selected as an $F_{4.5}$ line in the San Luis Valley at Center, CO, in 2003 and assigned experimental line number CO03W239. Thunder CL has shown superior grain yield under both nonirrigated and irrigated production conditions in eastern Colorado. Thunder CL carries the *Als1* gene conferring tolerance to imazamox herbicide, possesses moderate resistance to wheat streak mosaic virus, stripe rust (caused by *Puccinia striiformis* Westend. f. sp. tritici Eriks.), and stem rust (caused by *Puccinia graminis* Pers.:Pers. f. sp. tritici Eriks. & E. Henn), and shows superior milling and bread baking quality attributes.

Methods

Thunder CL was developed using the single-seed descent breeding procedure. All early-generation population development was done in the greenhouse or an irrigated field-

testing location at Fort Collins, CO. The cross between the parents, designated as cross-population X001725, was made in the greenhouse in fall 2000. The F_1 seed was harvested in January 2001 and planted in a field nursery in mid-February 2001. Seed from the F_1 plants was harvested in bulk in July 2001. A subsample of approximately 150 F_2 seeds was vernalized in a cold room for 8 wk at 2°C before planting in the greenhouse in October 2001. A single seed was harvested from each F_2 plant and vernalized for planting the F_3 generation in the greenhouse in March 2002. A single seed was harvested from each F_3 plant in June 2002 and vernalized for planting the F_4 in the greenhouse in October 2002. A single spike was harvested from each of the 79 F_4 plants in February 2003. Following vernalization, seedlings were hand-transplanted in May 2003 to a field nursery in the San Luis Valley at Center, CO. On the basis of visual observations of uniformity, Thunder CL was selected as an $F_{4.5}$ line in early September 2003 and assigned experimental designation CO03W239.

Thunder CL was evaluated in eastern Colorado in a preliminary yield trial in 2004, advanced yield trials in 2005, the CSU Elite Trial from 2006 to 2008, statewide nonirrigated and irrigated variety trials from 2006 to 2008, and the Southern Regional Performance Nursery (SRPN) in 2007 and 2008. Seed purification of Thunder CL was done by headrow progeny purification beginning with harvest of a group of visually uniform headrows grown under irrigation at Fort Collins in 2006. Progeny plots from these headrows were grown at Fort Collins in 2007 and treated with an aqueous solution of imazamox herbicide (105 g active ingredient ha⁻¹). Following NaOH testing (Ram et al., 2002) to confirm kernel color purity, seed harvested from 19 progeny plots was bulked to form Breeder seed to plant a 1.6-ha Foundation seed increase in 2008.

All statistical analyses were done using SAS-JMP Version 7.0.2 (SAS Institute, Cary, NC). Agronomic, disease resistance, and end-use quality data were analyzed by the Student's paired *t* test procedure. Yield and grain volume weight data from the CSU Elite Trial and statewide variety trials were subjected to combined analysis of variance across location-years. Only entries common to the trials across all years were included. Combined analyses were also done according to a mixed model with genotypes and location-year combinations as fixed factors and replications within location-year combinations as a random factor. Tukey's HSD test ($\alpha = 0.05$) was used to compare the least squares means for the genotype effects.

Characteristics

Agronomic and Botanical Description

Thunder CL is an awned, white-glumed, hard white winter wheat. Thunder CL has medium-early maturity, 143.2 d to heading from 1 January, 2.0 d earlier ($P < 0.05$; $n = 10$) than 'Hatcher' (PI 638512; Haley et al., 2005) and 2.5 d later ($P < 0.05$) than 'Above' (PI 631449; Haley et al., 2003). Plant height of Thunder CL is medium-short (67.0 cm; $n = 53$), similar ($P > 0.05$) to Hatcher and Above. Coleoptile length of Thunder CL (74.1 mm; $n = 10$) is similar to that

of Hatcher (77.7 mm, $P > 0.05$) and shorter than that of Above (85.5 mm, $P < 0.05$). Straw strength of Thunder CL is good (3.5 score, $n = 8$; 1 = erect to 9 = flat scale), similar to 'Bond CL' (PI 639924; Haley et al., 2006) (5.4 score, $P > 0.05$) and better than Hatcher (7.3 score, $P < 0.05$). No objective data are available for winterhardiness of Thunder CL, but field observations and performance under extremely dry soil conditions during recent winters in Colorado suggest that it is at least adequate for successful production in the central Great Plains region.

Thunder CL has a prostrate juvenile plant growth habit with a green plant color at the boot stage and a coleoptile that lacks anthocyanin pigment. Flag leaves of Thunder CL are erect, not twisted, and show a waxy bloom at the boot stage. Thunder CL has middense (laxidense), inclined, and tapering heads with white awns. Thunder CL has white, nonpubescent glumes that are medium length and medium width with oblique, narrow shoulders and narrow, acuminate beaks. Thunder CL has kernels that are ovate, white, and hard textured with a medium length noncolored brush, a rounded cheek, a narrow and shallow crease, a midsize germ, and a medium brown phenol reaction.

Disease and Insect Resistance

Thunder CL has been characterized for disease and insect resistance in Colorado and through cooperative evaluations of the USDA Regional Testing Program. Thunder CL is susceptible to moderately susceptible to stem rust (races QFCS, QTHJ, RCRS, RKQQ, TPMK, TTTT, and TTKSK) in greenhouse seedling evaluations. It displayed a moderately susceptible infection response with reduced disease severity (ranging from 20 to 40%, compared with 80% for susceptible checks) in field stem rust nurseries at St. Paul, MN, between 2006 and 2008. Thunder CL expresses the pseudo-black chaff trait in some environments. The low field stem rust severity and the pseudo-black chaff trait suggest that Thunder CL carries the *Sr2* gene for adult plant stem rust resistance. Microsatellite markers *gwm533* and *stm559tgag* that are associated with *Sr2* (Hayden et al., 2004) are present in Thunder CL. Greenhouse seedling evaluations with leaf rust (*Puccinia triticina* Eriks.) suggest that Thunder CL is susceptible to most common leaf rust races (MCRK, THBJ, MJB, MHDS, KFB, TNRJ, MFPSC, and mLDSB) while a resistant reaction to race TGBG suggests that Thunder CL carries the *Lr14a* resistance gene. Under natural field infection with unknown leaf rust races in Colorado and western Kansas in 2007 and 2008, Thunder CL was moderately susceptible (5.0 score, 1 = resistant and 9 = susceptible, $n = 5$), similar to Hatcher (4.4 score, $P > 0.05$) and more resistant than Above (8.0 score, $P < 0.05$). In greenhouse seedling evaluations under low temperatures, Thunder CL was consistently susceptible (infection types 8 to 9) to races PST-17, PST-37, PST-45, PST-100, and PST-116 of stripe rust. In greenhouse adult-plant tests under higher temperatures, Thunder CL was resistant (infection types 2 to 3) to races PST-45, PST-116, and PST-127. In field tests under natural stripe rust infection in 2007 and 2008, Thunder CL was resistant (infection types 2 to 3) with 20 to 30% severities near Pullman, WA, in both years (susceptible checks had infection type 8 and 80–100%

severities). Under natural field infection dominated by races PST-100 and PST-131 in Colorado in 2007, Thunder CL was moderately resistant (2.7 score, 1 = resistant and 9 = susceptible, $n = 6$), similar to Hatcher (2.8 score, $P > 0.05$) and more resistant than Above (7.6 score, $P < 0.05$). The susceptibility of seedlings at low temperatures and resistance of adult plants in greenhouse and field tests at higher temperatures suggest that Thunder CL has high temperature adult-plant resistance to stripe rust.

Other evaluations in Colorado or through the USDA Regional Testing Program have shown that Thunder CL is moderately resistant to wheat streak mosaic virus, susceptible to Barley yellow dwarf virus and wheat soilborne mosaic virus, heterogeneous for resistance to a collection of endemic biotypes of the Hessian fly [*Mayetiola destructor* (Say)] collected in Kansas, and susceptible to greenbug Biototype E [*Schizaphis graminum* (Rondani)]. In greenhouse seedling screening tests in Colorado, Thunder CL was resistant to Russian wheat aphid (*Diuraphis noxia* Kurdjumov) Biototype 1 and susceptible to Russian wheat aphid Biototype 2.

Field Performance

Thunder CL was tested at 25 trial locations of the CSU Elite Trial during 2006 (5 locations), 2007 (11 locations), and 2008 (9 locations). In the combined analysis across years, grain yield of Thunder CL was the third highest in the trials (2861 kg ha⁻¹), similar ($P > 0.05$) to 'Bill Brown' (PI 653260; Haley et al., 2008) (3029 kg ha⁻¹), Hatcher (2950 kg ha⁻¹), and the imazamox-tolerant checks Bond CL (2818 kg ha⁻¹) and Above (2760 kg ha⁻¹). In these trials, Thunder CL had average grain volume weight (763 kg m⁻³), similar to Hatcher (768 kg m⁻³, $P > 0.05$) and greater than ($P < 0.05$) Above (752 kg m⁻³) and Bond CL (747 kg m⁻³).

Thunder CL was tested at 28 trial locations of the nonirrigated Colorado Uniform Variety Performance Trial during 2006 (11 locations), 2007 (11 locations), and 2008 (6 locations). In the combined analysis across years, grain yield of Thunder CL (2784 kg ha⁻¹) was less than Hatcher (2945 kg ha⁻¹, $P < 0.05$), similar ($P > 0.05$) to 'Ripper' (PI 644222; Haley et al., 2007) (2817 kg ha⁻¹), Bill Brown (2793 kg ha⁻¹), and the imazamox-tolerant checks Bond CL (2761 kg ha⁻¹) and Above (2750 kg ha⁻¹), and greater than 'Danby' (PI 648010) (2669 kg ha⁻¹, $P = 0.06$) and 'Trego' (PI 612576; Martin et al., 2001) (2635 kg ha⁻¹, $P < 0.05$). In these trials, Thunder CL had below-average grain volume weight (747 kg m⁻³), slightly less than Hatcher (759 kg m⁻³, $P < 0.05$),

similar to Above (744 kg m⁻³, $P > 0.05$), and greater than Bond CL (740 kg m⁻³, $P < 0.05$).

Thunder CL was tested at nine trial locations of the Colorado Irrigated Variety Performance Trial during 2006 (three locations), 2007 (three locations), and 2008 (three locations). In the combined analysis across years, grain yield of Thunder CL (5767 kg ha⁻¹) was similar ($P > 0.05$) to Bond CL (6002 kg ha⁻¹), 'TAM 111' (PI 631352; Lazar et al., 2004) (5889 kg ha⁻¹), and Bill Brown (5886 kg ha⁻¹), and greater ($P < 0.05$) than 'Prairie Red' (PI 605390; Quick et al., 2001) (5360 kg ha⁻¹). In these trials, Thunder CL had average grain volume weight (761 kg m⁻³), less than ($P < 0.05$) TAM 111 (772 kg m⁻³) and Bill Brown (769 kg m⁻³), and greater than Bond CL (747 kg m⁻³, $P < 0.05$).

Thunder CL was tested in the 2007 and 2008 SRPN. Averaged across 10 locations in the High Plains region, Thunder CL was the 24th highest yielding entry in 2007 (3755 kg ha⁻¹; 50 total entries) and the 16th highest entry in 2008 (3722 kg ha⁻¹; 50 total entries).

End-Use Quality

Milling and bread baking characteristics of Thunder CL were determined using approved methods of the American Association of Cereal Chemists (AACC, 2000) in the CSU Wheat Quality Laboratory from multiple grain samples from the 2005, 2006, and 2007 seasons. Hatcher, Above, and Danby were included as checks in these evaluations. Values for milling-related variables were generally good for Thunder CL relative to the checks, with comparable kernel characteristics, flour extraction, and grain protein concentration (Table 1). On the basis of single kernel characterization system analysis, Thunder CL had lower kernel weight than Hatcher and Above with slightly harder kernel texture than Hatcher. Wheat ash and Brabender Quadrumat Senior

Table 1. Milling, dough mixing, and bread baking characteristics of wheat cultivars Thunder CL, Above, Danby, and Hatcher across multiple evaluations from the 2005, 2006, and 2007 crop seasons in Colorado.

Trait	Comparisons	Thunder CL	Above	Danby	Hatcher
SKCS [†] kernel weight (mg)	23	26.6	27.7*	26.6 ns	28.3*
SKCS kernel diameter (mm)	22	2.52	2.56 ns [‡]	2.49 ns	2.56 ns
SKCS kernel hardness index (score)	22	68.5	70.3 ns	71.1 ns	65.4*
Wheat protein (g kg ⁻¹)	22	138	145*	149*	139 ns
Wheat ash (g kg ⁻¹)	22	14.9	15.7*	14.4*	15.4 ns
Flour extraction (g kg ⁻¹)	21	661	641*	654 ns	654 ns
Mixograph peak time (min)	21	5.1	2.8*	2.8*	4.5*
Mixograph peak width (%)	21	22.2	18.2*	18.3*	20.2*
Mixograph right width (% at 2 min)	16	12.6	8.9*	8.5*	13.5 ns
Mixograph tolerance score [§]	21	3.7	1.3*	1.0*	3.8 ns
Bake water absorption (g kg ⁻¹)	20	650	659 ns	661*	657 ns
Bake mix time (min)	20	4.5	2.4*	2.4*	3.6*
Loaf volume (L)	20	1.05	0.86*	0.92*	0.99*
Crumb grain (score) [§]	20	4.3	1.8*	2.0*	3.9*

*Significance of the difference between Thunder CL and the check cultivar based on a Student's paired t test procedure at the 0.05 probability level.

[†]SKCS, single kernel characterization system.

[‡]ns, not significant.

[§]Mixograph tolerance and crumb grain score scales: 6 = outstanding, 0 = unacceptable.

(C.W. Brabender, South Hackensack, NJ) flour extraction were comparable to the checks and generally within the range of acceptability. Values for baking-related variables were generally superior for Thunder CL compared with Hatcher and especially Above and Danby (Table 1). In mixograph (National Manufacturing, Lincoln, NE) tests optimized for water absorption, Thunder CL had longer mixing time and greater curve width at peak than the three checks. The mixograph curve width 2 min after peak and subjective mixograph tolerance score were also greater for Thunder CL compared with Above and Danby, although similar to Hatcher. In straight-dough pup loaf baking tests, Thunder CL had similar bake water absorption and longer bake mix time and greater loaf volume and crumb grain score compared to the three checks.

Grain polyphenol oxidase (PPO) concentration and yellow alkaline noodle color stability of Thunder CL, Trego, and 'TAM 107' (PI 495594; Porter et al., 1987) were estimated from four intraregional production zone composites from the 2007 SRPN. Values for the change in noodle L* value (brightness) value between 0 and 24 h were similar ($P > 0.05$) for Thunder CL (-14.9), Trego (-14.7), and TAM 107 (-14.4). Spectrophotometer absorbance (475 nm) values for grain PPO concentration of Thunder CL (0.82) were higher than both Trego (0.73, $P = 0.07$) and TAM 107 (0.67, $P < 0.05$).

Availability

Thunder CL contains a patented herbicide tolerance trait owned by BASF Corporation (Florham Park, NJ) that confers tolerance to imidazolinone herbicides, such as imazamox. Any use of Thunder CL requires a Material Transfer Agreement (for research use only) or a Commercial License to the trait, as well as permission from the originator. Contact the corresponding author for all seed requests. The corresponding author will forward the request for seed to BASF Corporation. No seed will be distributed for 20 yr from the date of release without written permission from both BASF and Colorado State University.

The Colorado Agricultural Experiment Station will maintain Breeder seed of Thunder CL. Multiplication and distribution rights of other classes of certified seed have been transferred from the Colorado Agricultural Experiment Station to the Colorado Wheat Research Foundation, 7100 S. Clinton St. Suite 120, Centennial, CO 80112. Thunder CL has been submitted for U.S. Plant Variety Protection (PVP) under Public Law 91-577 with the Certification Only option. Recognized seed classes will include the Foundation, Registered, and Certified seed classes.

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