

Investigation of turfgrass seed-coating: Effects on storage, germination, and establishment

by

Parul Mandal

B.S., Chaudhary Charan Singh Haryana Agricultural University, 2019

M.S., Punjab Agricultural University, 2022

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Horticulture and Natural Resources
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2026

Abstract

Seed coating technology has the potential to improve seed germination, establishment, and storage, yet its effectiveness in turfgrass systems remains poorly understood and inconsistent. The objectives of this dissertation were to: 1) synthesize current knowledge of seed coating technologies in turfgrass (Chapter 1); 2) quantify short- and long-term storage temperature and condition effects on germination and seedling vigor of coated and noncoated cool-season seed (Chapters 2 and 3); and 3) evaluate the effects of seed coating, irrigation regimes, and soil types on turfgrass establishment in controlled and field environments (Chapters 4 and 5).

In Chapter 1, the literature review revealed mixed results, with coating improving germination in some studies but providing minimal-to-no benefit in others, highlighting the need for targeted research in turfgrass systems. Chapter 2 evaluated coated and noncoated cool-season turfgrass seed stored for one month at 4, 22, 42, 62, and 82 °C. Germination remained high at 4 to 42 °C but declined at 62 °C and was <1% at 82 °C, indicating that heat stress was the primary cause of seed deterioration. Chapter 3 determined the effect of seed coating in different storage environments, including refrigerator, indoor, and non-insulated shed conditions for up to two years. Seed stored in the shed exhibited the greatest germination losses, whereas refrigerated and indoor storage maintained stable germination. Moving from storage to establishment, Chapter 4 evaluated the effects of seed coating, irrigation regimes, and soil types under controlled conditions. Seed coating had minimal and inconsistent effects, whereas irrigation frequency and soil type exerted a major influence on successful establishment. Chapter 5 extended this work to field conditions by evaluating seed coating and irrigation frequency under an automated rainout

shelter. Seed coating did not improve emergence or turf cover; instead, optimal seeding timing and more frequent irrigation proved crucial for turfgrass establishment.

Overall, this work demonstrates that seed coating alone was not a reliable strategy for improving turfgrass germination, establishment, or storage. Maintaining cool, stable storage conditions and ensuring adequate soil moisture through proper irrigation are far more critical for preserving seed viability and ensuring successful turfgrass establishment.

Investigation of turfgrass seed-coating: Effects on storage, germination, and establishment

by

Parul Mandal

B.S., Chaudhary Charan Singh Haryana Agricultural University, 2019

M.S., Punjab Agricultural University, 2022

A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Horticulture and Natural Resources
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2026

Approved by:

Major professor
Dr. Ross Charles Braun

Copyright

© Parul Mandal 2026.

Abstract

Seed coating technology has the potential to improve seed germination, establishment, and storage, yet its effectiveness in turfgrass systems remains poorly understood and inconsistent. The objectives of this dissertation were to: 1) synthesize current knowledge of seed coating technologies in turfgrass (Chapter 1); 2) quantify short- and long-term storage temperature and condition effects on germination and seedling vigor of coated and noncoated cool-season seed (Chapters 2 and 3); and 3) evaluate the effects of seed coating, irrigation regimes, and soil types on turfgrass establishment in controlled and field environments (Chapters 4 and 5).

In Chapter 1, the literature review revealed mixed results, with coating improving germination in some studies but providing minimal-to-no benefit in others, highlighting the need for targeted research in turfgrass systems. Chapter 2 evaluated coated and noncoated cool-season turfgrass seed stored for one month at 4, 22, 42, 62, and 82 °C. Germination remained high at 4 to 42 °C but declined at 62 °C and was <1% at 82 °C, indicating that heat stress was the primary cause of seed deterioration. Chapter 3 determined the effect of seed coating in different storage environments, including refrigerator, indoor, and non-insulated shed conditions for up to two years. Seed stored in the shed exhibited the greatest germination losses, whereas refrigerated and indoor storage maintained stable germination. Moving from storage to establishment, Chapter 4 evaluated the effects of seed coating, irrigation regimes, and soil types under controlled conditions. Seed coating had minimal and inconsistent effects, whereas irrigation frequency and soil type exerted a major influence on successful establishment. Chapter 5 extended this work to field conditions by evaluating seed coating and irrigation frequency under an automated rainout

shelter. Seed coating did not improve emergence or turf cover; instead, optimal seeding timing and more frequent irrigation proved crucial for turfgrass establishment.

Overall, this work demonstrates that seed coating alone was not a reliable strategy for improving turfgrass germination, establishment, or storage. Maintaining cool, stable storage conditions and ensuring adequate soil moisture through proper irrigation are far more critical for preserving seed viability and ensuring successful turfgrass establishment.

Table of Contents

List of Figures	xii
List of Tables	xv
Appendix Figures.....	xviii
Appendix Tables	xx
Acknowledgements.....	xxiv
Dedication	xxv
Chapter 1 - Review of Literature: Seed Coating Technologies in Turfgrass Systems	1
Abstract.....	1
Introduction.....	2
History	4
Seed Coating Materials	5
Effect of Seed Coating on Germination and Establishment	10
Seed Viability and Longevity	18
Conclusions and Future Prospects	24
References.....	25
Chapter 2 - Short-Term Storage Temperature Effects on Coated and Noncoated Turfgrass Seed	32
Abstract.....	32
Introduction.....	33
Materials and Methods.....	35
Experimental design.....	35
Data collection	37
Seed moisture content	37
Germination speed and percentage	38
Seedling vigor	39
Data analysis	39
Results and Discussion	41
Seed moisture content	41
Germination parameters.....	43

Germination percentage	43
Germination speed	49
Seedling vigor	52
Pearson correlation analysis.....	54
Conclusions.....	56
References.....	58
Chapter 3 - The Influence of Long-term Storage Conditions on Coated and Noncoated Cool-	
Season Turfgrass Seed Germination and Seedling Vigor.....	62
Abstract	62
Introduction.....	63
Materials and Methods.....	66
Experimental design.....	66
Data collection	70
Seed moisture content	70
Germination rate and percent.....	70
Seedling vigor	73
Data analysis	73
Results.....	74
Storage environment	74
Seed moisture content	76
Germination	81
Germination speed	86
Seedling vigor	89
Pearson correlation analysis.....	94
Additional parameters	94
Discussion.....	95
Seed moisture content	95
Germination	97
Germination speed	99
Seedling vigor	100
Conclusions.....	102

References.....	104
Chapter 4 - Effects of Seed Coating, Irrigation Regimes, and Soil Texture on Turfgrass	
Establishment in Controlled Environment.....	108
Abstract.....	108
Introduction.....	109
Materials and Methods.....	111
Experiment design and management	111
Seeding.....	113
Irrigation	114
Data collection	115
Data analysis	116
Results.....	116
Seedling emergence	116
Turf cover.....	117
Visual turf cover	117
Percent green cover.....	119
Grid count	127
Discussion.....	130
Seedling emergence	130
Turf cover.....	131
Visual turf cover	131
Percent green cover and grid count.....	132
Conclusions.....	134
References.....	136
Chapter 5 - Effects of Seed Coating and Irrigation Frequency on Turfgrass Establishment in the	
Field	140
Abstract.....	140
Introduction.....	141
Materials and Methods.....	143
Experiment design and management	143
Seeding.....	145

Irrigation	146
Data collection	146
Data analysis	147
Results and Discussion	148
Weather conditions during establishment	148
Seedling emergence	149
Turf cover.....	151
Visual turf cover	151
Percent green cover and grid count.....	153
Conclusions.....	160
References.....	161
Chapter 6 - Summary	165
Appendix A - Additional Figures and Tables for Chapter 2.....	168
Appendix B - Additional Figures and Tables for Chapter 3.....	171
Appendix C - Additional Figures and Tables for Chapter 4.....	196
Appendix D - Additional Figures for Chapter 5	225

List of Figures

Figure 1.1. Coated turfgrass seeds (top) and respective noncoated turfgrass seed species counterparts underneath (bottom).	7
Figure 2.1. Interaction effect of seed coating and storage temperature on seed moisture content within each of the four cool-season turfgrass species in Experiment 1: (a) tall fescue, (b) Kentucky bluegrass, (c) strong creeping red fescue, and (d) perennial ryegrass. <i>Note:</i> Means within each species followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Statistical comparisons are not across species. ..	44
Figure 2.2. Interaction effect of seed coating and storage temperature on seed moisture content within each of the three cool-season turfgrass species in Experiment 2: (a) tall fescue, (b) Kentucky bluegrass, and (c) strong creeping red fescue. <i>Note:</i> Means within each species followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Statistical comparisons are not across species.	45
Figure 2.3. Quadratic regression of germination percentage in response to storage temperature for coated and noncoated seeds combined across all cool-season turfgrass species and both experiments ($n = 400$). <i>Note:</i> Points represent observed germination values at each storage temperature, and lines represent fitted quadratic regression models for each seed coating treatment. The coefficient of determination (R^2) and adjusted R^2 describe the goodness of fit of the regression model ($P < 0.001$).	48
Figure 2.4. Effects of seed coating on shoot and root length of tall fescue (TF), Kentucky bluegrass (KB), strong creeping red fescue (SCRF), and perennial ryegrass (PR) in Experiment 1. <i>Note:</i> Different letters on bars indicate significant differences among means within each species at $\alpha = 0.05$ according to Fisher's protected LSD test.	53
Figure 2.5. Effects of storage temperature on shoot and root length of tall fescue (TF), Kentucky bluegrass (KB), and strong creeping red fescue (SCRF) in Experiment 2. <i>Note:</i> Different letters on bars indicate significant differences among means within each species at $\alpha = 0.05$ according to Fisher's protected LSD test. Mean values represent back-transformed means; statistical analyses were performed on $\log(y + 0.5)$ -transformed data.	54
Figure 2.6. Pearson correlation matrix showing relationships among seed moisture content, germination, emergence, and seedling growth traits across Experiments 1 and 2. <i>Note:</i>	

SMC, seed moisture content (%); Germ, germination (%); Top, top germination percentage (%); MGT, mean germination time (d); DG ₅₀ , days to 50% germination (d); ADW, average seedling dry weight (mg); Shoot length (cm); Root length (cm). Values shown are Pearson correlation coefficients (<i>r</i>). Blue and red colors indicate positive and negative correlations, respectively, with darker colors representing stronger relationships. Only the lower triangle of the correlation matrix is displayed. *, **, and *** indicate statistical significance at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.	55
Figure 3.1. Interaction effects of coating × storage condition on seed moisture content (%) across storage durations in four cool-season turfgrass species (Run 1 – Top and Run 2 – Bottom). Note: Year 0 represents baseline seed moisture content prior to storage and is not included in the coating × storage condition interaction analysis, instead it is the coating main effect for Year 0 shown in the figure. Points represent treatment means for each species, year, and storage condition. Means followed by different letters are significantly different according to Fisher’s protected LSD test ($P \leq 0.05$) within each species and each year.	78
Figure 3.2. Effect of coating × storage condition interaction on germination (%) of coated and noncoated tall fescue and Kentucky bluegrass across storage durations (Run 1).....	83
Figure 3.3. Effect of coating × storage condition interaction on germination (%) of coated and noncoated tall fescue and Kentucky bluegrass across storage durations (Run 2). Means within a storage duration and species followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher’s protected LSD test ($P < 0.05$). Note: See Figure 2 for a description of treatments and statistical comparisons.	83
Figure 3.4. Pearson correlation matrix among seed moisture content, germination, germination speed, and seedling growth traits in the long-term storage experiment, pooled across both runs and all species. Note: SMC, seed moisture content (%); Germ, germination (%); Top, top germination percentage (%); MGT, mean germination time (d); DG ₅₀ , days to 50% germination (d); ADW, average seedling dry weight (mg); Shoot length (cm); Root length (cm). Values shown are Pearson correlation coefficients (<i>r</i>). Blue and orange colors indicate positive and negative correlations, respectively, with darker colors representing stronger relationships. Only the lower triangle of the correlation matrix is displayed. *, **, and *** indicate statistical significance at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.	95

Figure 4.1. Effect of irrigation amount on visual turf cover (%) of perennial ryegrass, tall fescue, and strong creeping red fescue in Experiment 1 across days after planting (DAP). <i>Note:</i> Letters within each DAP within each species indicate significant differences according to Fisher's protected LSD test ($\alpha = 0.05$).....	121
Figure 4.2. Effect of soil type on visual turf cover (%) of perennial ryegrass, tall fescue, strong creeping red fescue, and Kentucky bluegrass in Experiment 2 across days after planting (DAP). <i>Note:</i> Letters within each DAP within each species indicate significant differences according to Fisher's protected LSD test ($\alpha = 0.05$).....	122
Figure 4.3. Effect of the irrigation frequency $\times$ soil type interaction on visual turf cover (%) of bermudagrass across days after planting (DAP) in Experiment 3. <i>Note:</i> Letters within each DAP indicate significant differences according to Fisher's protected LSD test ($\alpha = 0.05$).	123
Figure 4.4. Effect of coating and irrigation amount on turf cover (%) from grid counts in perennial ryegrass and tall fescue across days after planting (DAP) in Experiment 1. <i>Note:</i> Bars represent irrigation amount (2.5 mm d ⁻¹ and 5.1 mm d ⁻¹), and lines represent coating treatments (coated vs. noncoated). Letters within each DAP indicate significant differences ($\alpha = 0.05$).....	129
Figure 4.5. Effect of soil type on grid count (turf cover %) at 15, 25, 35, and 45 days after planting in four cool-season turfgrass species in Experiment 2. <i>Note:</i> Letters within each DAP indicate significant differences ($\alpha = 0.05$).	129

List of Tables

Table 1.1. List of seed coating materials and their impact on germination and establishment of turfgrass and other grass and plant crops, listed chronologically within each crop section.	14
Table 1.2. Overview of seed storage studies: Effects on seed germination and viability of turfgrass and other grass and plant crops, listed chronologically within each crop species.	22
Table 2.1. Species, cultivars or blends, coating composition, and seed companies' information.	37
Table 2.2. Effect of seed coating and storage temperature on germination percentage of four cool-season turfgrass species in Experiment 1.	47
Table 2.3. Effect of seed coating and storage temperature on germination percentage of three cool-season turfgrass species in Experiment 2.	48
Table 2.4. Interaction effect of seed coating and storage temperature on germination speed (DG50 and MGT) in Kentucky bluegrass and perennial ryegrass in Experiment 1.	51
Table 2.5. Interaction effect of seed coating and storage temperature on germination speed (DG50 and MGT) in tall fescue and Kentucky bluegrass in Experiment 2.	51
Table 3.1. Minimum, maximum, and mean temperatures recorded under different storage conditions for Run 1 and Run 2.	68
Table 3.2. Minimum, maximum, and mean relative humidity recorded under different storage conditions for Run 1 and Run 2.	69
Table 3.3. Effects of coating and storage condition on seed moisture content (%) of cool-season turfgrass species across years in Run 1.	79
Table 3.4. Effects of coating and storage condition on seed moisture content (%) of cool-season turfgrass species across years in Run 2.	80
Table 3.5. Effects of coating and storage condition on germination (%) of cool-season turfgrass species across years in Run 1.	84
Table 3.6. Effects of coating and storage condition on germination (%) of cool-season turfgrass species across years in Run 2.	85
Table 3.7. Interaction effects of coating × storage condition on mean germination time (days) of cool-season turfgrass species across years in Run 1.	87
Table 3.8. Interaction effects of coating × storage condition on mean germination time (days) of cool-season turfgrass species across years in Run 2.	88

Table 3.9. ANOVA for main effects (coating and storage condition) and their interaction on shoot length (mm) of cool-season turfgrass species across years in both Runs 1 and 2.....	91
Table 3.10. Interaction effects of coating $\times$ storage condition on shoot length (mm) of cool-season turfgrass species across years in Runs 1 and 2.....	92
Table 3.11. ANOVA for main effects (coating and storage condition) and their interaction on root length (mm) of cool-season turfgrass species across storage durations in Run 1 and Run 2.....	93
Table 4.1. Details of species investigated and treatment factors in Experiments 1, 2, and 3.	113
Table 4.2. Pure live seed (PLS) rates and seed weights used per pot for turfgrass species in Experiments 1, 2 and 3.....	114
Table 4.3. Analysis of variance (ANOVA) <i>p</i> values for visual turf cover at 10, 20, 30, 40 and 50 DAP in multiple cool-season turfgrasses in Experiment 1 (Seed coating $\times$ Irrigation amount) and Experiment 2 (Seed coating $\times$ Irrigation frequency $\times$ Soil type).	120
Table 4.4. Analysis of variance (ANOVA) <i>p</i> values for visual turf cover at 15, 25, 35 and 45 days after planting in bermudagrass (warm-season turfgrass) in Experiment 3 (Seed coating $\times$ Irrigation frequency $\times$ Soil type).	121
Table 4.5. Analysis of variance (ANOVA) <i>p</i> values for percent green cover at 10, 20, 30, 40 and 50 days after planting in perennial ryegrass, tall fescue, strong creeping red fescue and Kentucky bluegrass in Experiment 1 and Experiment 2.....	125
Table 4.6. Analysis of variance (ANOVA) <i>p</i> values for percent green cover at 15, 25, 35 and 45 days after planting in bermudagrass in Experiment 3.....	126
Table 5.1. Species, cultivars or blends, coating composition, and seed companies' information.	144
Table 5.2. Pure live seed (PLS) rates and seed weight used for turfgrass species in Experiments 1 and 2.....	146
Table 5.3. Air temperature ($^{\circ}$ C) and relative humidity (%) during Experiments 1 and 2 in 2024 and 2025.....	149
Table 5.4. Mean seedling emergence time of turfgrass species as influenced by seed coating and irrigation frequency in Experiments 1 and 2.....	151

Table 5.5. Effects of seed coating and irrigation frequency on visual turf cover (%) of turfgrass species (cool- and warm- season) at 10, 20, 30, and 35 days after planting (DAP) in Experiment 1.....	154
Table 5.6. Effects of seed coating and irrigation frequency on visual turf cover (%) of turfgrass species (cool-season) at 15, 25, 35, and 45 days after planting (DAP) in Experiment 2....	155
Table 5.7. Effects of seed coating and irrigation frequency on percent green cover (%) of turfgrass species (cool- and warm- season) at 10, 20, 30, and 35 days after planting (DAP) in Experiment 1.....	156
Table 5.8. Effects of seed coating and irrigation frequency on percent green cover (%) of turfgrass species (cool-season) at 15, 25, 35, and 45 days after planting (DAP) in Experiment 2.....	157
Table 5.9. Effects of seed coating and irrigation frequency on grid count (turf cover %) of turfgrass species (cool- and warm- season) at 10, 20, 30, and 35 days after planting (DAP) in Experiment 1.....	158
Table 5.10. Effects of seed coating and irrigation frequency on grid count (turf cover %) of turfgrass species (cool-season) at 15, 25, 35, and 45 days after planting (DAP) in Experiment 2.....	159

Appendix Figures

Figure A.1. Noncoated and coated turfgrass seed samples used in the short-term storage experiments. Noncoated seed is shown on the left, while coated seed samples are shown in the middle and right Petri dishes.....	169
Figure B.1. Seed sample preparation and weighing for seed moisture content determination. (A) Labeled seed envelopes organized prior to weighing. (B) Coated turfgrass seed weighed using an analytical balance before seed moisture content analysis.	172
Figure B.2. Germination testing and data collection procedure for turfgrass seed. (A) Petri dishes placed inside the growth chamber for germination (B) Germinated seeds identified based on visible radicle and plumule emergence. (C) Close-up view of germinated seeds on blotter paper. (D) Daily germination counting procedure, in which germinated seeds were counted, removed, and the Petri dishes were placed back to the growth chamber for continued evaluation over 28 days.	173
Figure B.3. Paper towel method for seedling vigor evaluation of turfgrass seed. (A) Germination paper moistened before seed placement. (B) Seeds placed on labeled germination paper according to treatment and replication. (C) Prepared rolled towels enclosed in plastic bags to maintain moisture during incubation. (D) Rolled towel samples placed upright in containers inside the growth chamber for seedling development.	174
Figure B.4. Seedling vigor measurements of turfgrass seed after 21 days of incubation in a growth chamber. (A) Germinated seedlings arranged on moist germination paper before measurement. (B) Root and shoot lengths measured using a digital vernier caliper to quantify seedling growth.....	175
Figure C.1. Greenhouse experimental setup for evaluating seed coating, irrigation regime, and soil type effects on turfgrass establishment at the Throckmorton Plant Science Center greenhouses, Kansas State University.	197
Figure C.2. Greenhouse study preparation. (A) Pots lined with cloth fabric before adding sand. (B) Pots filled with different soil types. (C) Experiment 1 pots arranged to evaluate the effects of seed coating and irrigation amount using the same soil type. (D) Experiment 2 pots arranged to evaluate the effects of seed coating and irrigation frequency across different soil types.....	198

Figure C.3. Greenhouse turfgrass establishment in Experiments 1, 2, and 3. (A) Experiment 1 evaluating seed coating and irrigation amount effects. (B) Experiment 2 evaluating seed coating and irrigation frequency effects across soil types. (C) Experiment 3 evaluating bermudagrass establishment under different soil type and treatment combinations.	199
Figure C.4. Digital image collection for turfgrass cover assessment (percent green cover) using digital camera.	200
Figure C.5. Greenhouse turfgrass cover assessment using a grid-count method. A 9×9 grid frame with 81 intersections was placed over each pot, and turfgrass presence at each intersection was recorded to calculate turfgrass cover.	201
Figure C.6. Effects of irrigation frequency $\times$ soil type and seed coating $\times$ soil type interactions on percent green cover (%) in tall fescue and strong creeping red fescue at selected days after planting (DAP) in Experiment 2. <i>Note:</i> Bars represent treatment means. Irrigation frequency treatments were daily and every 2 d, and soil types were sand and silt loam. Coating treatments included coated and noncoated seed. Letters above bars within each panel indicate significant differences among treatments at each DAP according to Fisher's protected LSD test ($\alpha = 0.05$). Percent green cover was measured using digital image analysis.	202
Figure D.1. Automated rainout shelter used for field experiments at Rocky Ford.	226
Figure D.2. Field plot layout and seeding procedure at Rocky Ford. (A) Prepared experimental plots under the automated rainout shelter. (B) Turfgrass seed manually broadcast within each plot.	227
Figure D.3. View of turfgrass seed on the soil surface after seeding. (A) Noncoated tall fescue seed. (B) Coated Kentucky bluegrass seed. (C) Coated tall fescue seed.	228
Figure D.4. Turfgrass cover assessment using a grid-count method. (A) Grid frame with 100 intersections placed over an individual field plot. (B) Turfgrass presence recorded at each grid intersection to calculate percent turfgrass cover.	229

Appendix Tables

Table A.1. Effect of seed coating and storage temperature on germination speed (DG50 and MGT) of multiple cool-season turfgrass species in Experiment 1.	170
Table B.1. Effects of coating, storage condition, and their interaction on seed moisture content (%) of cool-season turfgrass species across years in Run 1.....	176
Table B.2. Effects of coating, storage condition, and their interaction on seed moisture content (%) of cool-season turfgrass species across years in Run 2.....	177
Table B.3. Effects of coating, storage condition, and their interaction on germination (%) of cool-season turfgrass species across years in Run 1.	178
Table B.4. Effects of coating, storage condition, and their interaction on germination (%) of cool-season turfgrass species across years in Run 2.	179
Table B.5. Effects of coating, storage condition, and their interaction on mean germination time (days) of cool-season turfgrass species across years in Run 1.....	180
Table B.6. Effects of coating, storage condition, and their interaction on mean germination time (days) of cool-season turfgrass species across years in Run 2.....	181
Table B.7. Effects of coating, storage condition, and their interaction on days to 50% germination (DG ₅₀) of cool-season turfgrass species across years in Run 1.	182
Table B.8. Effects of coating, storage condition, and their interaction on days to 50% germination (DG ₅₀) of cool-season turfgrass species across years in Run 2.	183
Table B.9. Effects of coating, storage condition, and their interaction on shoot length (mm) of cool-season turfgrass species across years in Run 1.	184
Table B.10. Effects of coating, storage condition, and their interaction on shoot length (mm) of cool-season turfgrass species across years in Run 2.	185
Table B.11. Effects of coating, storage condition, and their interaction on root length (mm) of cool-season turfgrass species across years in Run 1.	186
Table B.12. Effects of coating, storage condition, and their interaction on root length (mm) of cool-season turfgrass species across years in Run 2.	187
Table B.13. Effects of coating, storage condition, and their interaction on hillslope of cool-season turfgrass species across years in Run 1.	188

Table B.14. Effects of coating, storage condition, and their interaction on hillslope of cool-season turfgrass species across years in Run 2.	189
Table B.15. Effects of coating, storage condition, and their interaction on top (%) of cool-season turfgrass species across years in Run 1.	190
Table B.16. Effects of coating, storage condition, and their interaction on top (%) of cool-season turfgrass species across years in Run 2.	191
Table B.17. Effects of coating, storage condition, and their interaction on average fresh weight (mg) of cool-season turfgrass species across years in Run 1.	192
Table B.18. Effects of coating, storage condition, and their interaction on average fresh weight (mg) of cool-season turfgrass species across years in Run 2.	193
Table B.19. Effects of coating, storage condition, and their interaction on average dry weight (mg) of cool-season turfgrass species across years in Run 1.	194
Table B.20. Effects of coating, storage condition, and their interaction on average dry weight (mg) of cool-season turfgrass species across years in Run 2.	195
Table C.1. Effect of seed coating, irrigation amount, and their interaction on seedling emergence of cool-season turfgrass species in Experiment 1	203
Table C.2. Effect of seed coating, irrigation frequency, soil type, and their interaction on seedling emergence of cool-season turfgrass species in Experiment 2.	204
Table C.3. Interaction effect of irrigation frequency and soil type on seedling emergence of cool-season turfgrass species in Experiment 2.	205
Table C.4. Effect of seed coating, irrigation frequency, soil type, and their interaction on seedling emergence of bermudagrass in Experiment 3.	206
Table C.5. Interaction effect of irrigation frequency and soil type on seedling emergence of bermudagrass in Experiment 3.	206
Table C.6. Effect of seed coating, irrigation amount, and their interaction on visual turf cover (%) at 10, 20, 30, 40, and 50 days after planting in perennial ryegrass, tall fescue, and strong creeping red fescue in Experiment 1.	207
Table C.7. Interaction effect of seed coating and irrigation amount on visual turf cover (%) at 10, 20, 30, 40, and 50 days after planting in strong creeping red fescue in Experiment 1.	208

Table C.8. Effect of seed coating, irrigation frequency and soil type, and their interaction on visual turf cover (%) at 10, 20, 30, 40, and 50 days after planting in perennial ryegrass and tall fescue in Experiment 2.....	209
Table C.9. Effect of seed coating, irrigation frequency and soil type, and their interaction on visual turf cover (%) at 10, 20, 30, 40, and 50 days after planting in strong creeping red fescue and Kentucky bluegrass in Experiment 2.	210
Table C.10. Interaction effect of seed coating and soil type on visual turf cover (%) at 10, 20, 30, 40, and 50 days after planting in strong creeping red fescue in Experiment 2.	211
Table C.11. Effect of seed coating, irrigation frequency, soil type, and their interaction on visual turf cover (%) at 15, 25, 35 and 45 days after planting in bermudagrass in Experiment 3.	212
Table C.12. Effect of seed coating, irrigation amount, and their interaction on percent green cover (%) at 10, 20, 30, 40, and 50 days after planting in perennial ryegrass, tall fescue, and strong creeping red fescue in Experiment 1.....	213
Table C.13. Effect of seed coating, irrigation frequency, soil type, and their interaction on percent green cover (%) at 10, 20, 30, 40, and 50 days after planting in perennial ryegrass and tall fescue in Experiment 2.....	214
Table C.14. Effect of seed coating, irrigation frequency, soil type, and their interaction on percent green cover (%) at 10, 20, 30, 40, and 50 days after planting (DAP) in strong creeping red fescue and Kentucky bluegrass in Experiment 2.	215
Table C.15. Effect of seed coating, irrigation frequency, soil type, and their interaction on percent green cover (%) at 15, 25, 35 and 45 days after planting in bermudagrass in Experiment 3.	216
Table C.16. Interaction effect of irrigation frequency $\times$ soil type on percent green cover (%) at 15, 25, 35 and 45 days after planting in bermudagrass in Experiment 3.	217
Table C.17. Effect of seed coating, irrigation amount, and their interaction on grid count (%) at 15, 25, 35, and 45 days after planting in perennial ryegrass and tall fescue in Experiment 1.	218
Table C.18. Effect of seed coating, irrigation amount, and their interaction on grid count (%) at 15, 25, 35, and 45 days after planting in strong creeping red fescue and Kentucky bluegrass in Experiment 1.....	219

Table C.19. Interaction effect of seed coating × irrigation amount on grid count (turf cover %) at 15, 25, 35 and 45 days after planting in strong creeping red fescue in Experiment 1.	220
Table C.20. Effect of seed coating, irrigation frequency, soil type and their interactions on grid count (turf cover %) at 15, 25, 35, and 45 days after planting (DAP) in perennial ryegrass and tall fescue in Experiment 2.....	221
Table C.21. Effect of seed coating, irrigation frequency, soil type and their interactions on grid count (turf cover %) at 15, 25, 35, and 45 days after planting (DAP) in strong creeping red fescue and Kentucky bluegrass in Experiment 2.	222
Table C.22. Effect of seed coating, irrigation frequency, soil type and their interactions on grid count (turf cover %) at 15, 25, 35, and 45 days after planting in bermudagrass in Experiment 3.....	223
Table C.23. Interaction effect of irrigation frequency × soil type on grid count (turf cover %) at 15, 25, 35 and 45 days after planting in bermudagrass in Experiment 3.	224

Acknowledgements

No achievement is truly accomplished alone. I would like to thank the faculty, staff, and graduate students in the Department of Horticulture and Natural Resources at Kansas State University.

I sincerely thank my advisor, Dr. Ross Braun, for his guidance, patience, and continuous support throughout my Ph.D. journey. His mentorship has been invaluable in helping me grow as a researcher and strengthen my skills in turfgrass science. I am especially grateful for his thoughtful feedback, the time he spent reviewing my work, and guidance through each stage of my research. I also appreciate the Braun Turfgrass Lab for providing the resources and funding that supported my Ph.D. research.

I thank my committee members, Drs. Steve Keeley, Romulo Lollato, C. B. Rajasekhar, and Sunghun Park, for their guidance, support, and encouragement. I am also grateful to Wesley Howe for his help with my field studies at the Rocky Ford Turfgrass Research Center, and to the undergraduate students who assisted with my research.

Thanks to my lab mates, Emmanuel Nwachukwu, Alex Stanton, Muhammad Ammar Rafique, and Muhammad Usman Tanveer, for their assistance along the way. I also appreciate my friends, Mandeep Kaur, Sophie Awad, Ranveer Kaur, Parveen, Aprajita Jha, Thitikan Jirakittisonthon, Levi Dreiling and Rachel Rusten for their friendship and encouragement.

I am thankful to God for blessing me with a loving and supportive family. I am deeply grateful to my parents, Usha Mandal and Ram Kumar Mandal, and my siblings, Rabpreet Mandal and Vansh Mandal, for their love, prayers, and encouragement. Special thanks to my best friend, Pradeep Kumar, for his constant support, care, and encouragement throughout my academic journey.

Dedication

I dedicate this work to my loving parents, Usha Mandal and Ram Kumar Mandal, and to Pradeep Kumar.

Chapter 1 - Review of Literature: Seed Coating Technologies in Turfgrass Systems

Abstract

Seed coating technology has gained momentum in recent years as a potential method for enhancing germination and viability in agricultural crops. The global market for seed coating materials, including binders, fillers, and active additives, is rapidly expanding, reflecting increasing adoption across both developed and emerging economies. Seed coatings involve applying external materials to seeds to improve their handling, protection, and growth. The evolution of seed coating technology has led to the development of coatings that deliver various compounds to modify the microenvironment of individual seeds, such as pesticides, nutrients, absorbents, and plant growth regulators. This review synthesizes current knowledge of seed coating technologies in turfgrass systems, identifies key gaps, and outlines opportunities to optimize coating practices to improve seed germination, establishment, and storage. Although seed coating has shown potential to increase seed germination and viability in various agronomic and horticultural crops, research on turfgrass is not well defined. Some research has reported improvements in turfgrass germination and establishment, whereas others have shown minimal-to-no benefits. These mixed findings highlight the need to examine how coating materials, turfgrass species, and environmental conditions interact to influence seed performance. Future research should refine coating techniques, broaden evaluations across turfgrass species, and assess the effects of storage conditions on maintaining viability. Currently, it is advisable for turfgrass practitioners to exercise caution when considering the use of coated turfgrass seed, as its performance has been inconsistent. Further research into seed coatings is necessary to develop more reliable recommendations for practitioners in the turfgrass industry.

Introduction

The turfgrass industry comprises green spaces such as lawns, commercial properties, golf courses, sports fields, parks, sod farms, roadsides, and other urban green areas. Turfgrass covers approximately 31 to 40 million acres in the United States, ranging from no to high-input (e.g., irrigation, fertilizer, pesticides) maintained areas (Patton & Braun, unpublished data). The presence of turfgrass areas benefits society by providing a range of ecosystem services (Braun et al., 2024). To harness these benefits, it is essential to achieve rapid, uniform turfgrass establishment (Braun et al., 2023).

Successful turfgrass seeding establishment relies on seed germination (Jiang & Su, 2018). To improve seed germination and seedling growth of various plant species, seed enhancement technologies, such as post-harvest seed treatments or procedures (e.g., seed coating, film coating, encrusting, pelleting, priming, and inoculation), have gained significant traction as an additional agricultural technique (Halmer, 2008). These approaches include physical, chemical, or biological methods aimed at increasing seed germination, vigor, emergence, and tolerance to various biotic and abiotic stresses (Svejcar et al., 2022). More specifically, some seed enhancement technologies include priming, coating, pelleting, scarification, and disinfection (Brown et al., 2021).

Seed coating technology has become an important component of modern agricultural practices, enabling the precise application of potentially beneficial substances to seed surfaces (Gomes et al., 2025). Seed coating is a technique that involves applying external materials to seeds to improve their handling and protection, and, to some extent, enhance germination and plant establishment (Avelar et al., 2012; Pedrini et al., 2020). Seed coating techniques are rapidly expanding across emerging and developed economies, driving significant growth in the global

market for seed coatings-materials, such as binders, fillers, and other active additives. Due to trade secret or proprietary reasons, many companies may withhold information on seed coating ingredients and concentrations from their clientele and only provide general seed coating type statements, such as “limestone coating,” for example. In 2019, the market for these materials alone was valued at \$1.8 billion, and it is projected to reach nearly \$3.5 billion by 2030 (Markets & Markets, 2025). Since the early 2000s, seed coating technology has gradually gained traction in the turfgrass industry, with an increasing number of seed companies adopting it to promote better seed germination and turf establishment. Seed coatings may affect key seed traits, including seed germination, viability, longevity, moisture content, and dormancy in turfgrass species (Halmer, 2008; Scott, 1989).

Several studies suggested that seed coating is an effective method for enhancing seed germination and viability in agricultural and vegetable crops, including corn (*Zea mays* L.) and canola (*Brassica napus* L.) (Accinelli et al., 2016), rice (*Oryza sativa* L.) (Cortés-Rojas et al., 2021; Agake et al., 2021), wheat (*Triticum aestivum* L.) and tomato (*Lycopersicon esculentum* Mill.) (Bashan et al., 2002; Giordano et al., 2025; Pinto et al., 2019), castor (*Ricinus communis* L.) (Chandrika et al., 2019), soybean (*Glycine max* L.) (De Gregorio et al., 2017), common bean (*Phaseolus vulgaris* L.) (Campaña & Arias, 2020; Zvinavashe et al., 2021). Additionally, it may influence optimal conditions and duration for seed storage, a factor closely tied to seed viability and longevity (Ma, 2019). Despite the increasing availability of coated seed, little research has examined the effects of seed coating on germination, seedling emergence, and turfgrass establishment. This review evaluates the effects of seed coating technology on turfgrass germination, establishment, and storage longevity, compares responses with those of other grass and forage crops, and identifies key knowledge gaps and future research opportunities.

History

The origins of seed coating can be traced back to the 1930s when Germain's, a British seed company, first developed coatings for agricultural crops (Kaufman, 1991). Large-scale commercialization followed in the 1960s within the European greenhouse industry, where precision sowing required more uniform seed size and flowability (Kaufman, 1991). In the U.S., seed pelleting, a type of seed coating, was widely adopted in California during the 1970s. This shift was largely driven by the need for more efficient lettuce (*Lactuca sativa* L.) seed singulation during mechanical thinning (Hill, 1999). Seed pelleting marked a key milestone in the development of seed coating technology (Hill, 1999). By the 1980s, seed coating had gained sufficient attention, leading to early reviews such as that by Jeffs (1986), which summarized seed-coating techniques developed to improve agricultural production. This highlighted the growing interest in seed-coating technology as it expanded across agricultural systems. The commercial application of seed coating during this period was likely influenced by earlier research and development of seed-coating techniques, as well as by the increasing demand for more efficient and sustainable agricultural practices. In the late 1980s, Scott (1989) used seed coatings to improve the microenvironment of turfgrass and other plant seeds, and reviewed various seed coating materials (i.e., phosphate, lime, talc) and their effects on various grass and other species, i.e., orchard grass (*Dactylis glomerata* L.), Chewings fescue [*Festuca rubra* L. ssp. *commutata* Gaudin; syn. *F. rubra* ssp. *fallax* (Thuill.) Nyman], Yorkshire fog (*Holcus lanatus* L.), yarrow (*Achillea millefolium* L.), and rye (*Secale cereale* L.) establishment.

Studies on seed coating technologies in agricultural crops including corn, soybean, cotton (*Gossypium hirsutum* L.), rice, alfalfa (*Medicago sativa* L.), tobacco (*Nicotiana tabacum* L.) as well as vegetable crops such as onion (*Allium cepa* L.), tomato, cucumber (*Cucumis sativus* L.),

lettuce (*Lactuca sativa* L.), sugar beet (*Beta vulgaris* L.), carrot (*Daucus carota* L.), celery (*Apium graveolens* L.), and pepper (*Capsicum annuum* L.), and ornamental flowers including impatiens (*Impatiens walleriana* Hook. f.), marigold (*Tagetes erecta* L.), and petunia (*Petunia* × *atkinsiana* D. Don ex Loudon [*axillaris* × *integrifolia*]), continually increased through the 1990s (Taylor & Harman, 1990; Kaufman, 1991). Similarly, seed coating research in turfgrass species began in the 1990s, investigating species such as colonial bentgrass (*Agrostis capillaris* L.), red fescue (*Festuca rubra* L.), Kentucky bluegrass (*Poa pratensis* L.), and perennial ryegrass (*Lolium perenne* L.) by Newell (1997) and Greipsson (1999). In the 2000s, researchers studied various coatings treatments including macro- and micronutrients, plant growth regulators, growth stimulants, protection products, inoculants, and specialized polymers in various horticultural crops including carrot, celery, lettuce, onion, pepper, tomato, corn, sugar beet and several ornamental species including begonia (*Begonia* spp.), pansy (*Viola bicolor* Pursh), vinca [*Catharanthus roseus* (L.) G. Don] and verbena (*Verbena officinalis* L.) (Halmer, 2008). Overall, research has focused on seed enhancements and seed-coating equipment in the 21st century for agricultural and horticultural crops (Halmer, 2000; Pedrini et al., 2020). The advancement of seed coating technology highlights the role of innovation and research in agriculture and its positive impact on global food security and sustainability.

Seed Coating Materials

Seed coating involves applying materials to the seed surface, affecting both the seed and the seed–soil interface (Scott, 1989) (Figure 1.1). A wide range of substances is used as seed coating agents in the seed coating process (Pedrini, 2017). Over time, seed coating has undergone a significant transformation, shifting from altering seed size and shape to producing treated coatings that provide various compounds to modify the microenvironment of individual

seeds (Halmer, 2008). These compounds can include fungicides, insecticides, herbicides, micronutrients, macronutrients, growth regulators, surfactants, polymers, bird and rodent repellents, and chemicals that either stimulate or inhibit germination (Pedrini et al., 2020). Seed coating serves a multifaceted role in improving seed uniformity, seed quality, protecting against diseases and pests, promoting uniform germination, incorporating beneficial microbes, and improving seed handling and planting efficiency (Scott, 1989). It may also involve coating nutrients or growth-promoting substances to facilitate early seedling development (Taylor & Harman, 1990). Leinauer et al. (2010) reported that seed coating with ZEBA polymer, which contains starch-g-poly (2-propenamide-co-propenoic acid) potassium salt, can improve turfgrass seed performance under suboptimal conditions such as limited irrigation and lower seeding densities. The turfgrass species in the experiment included creeping bentgrass (*Agrostis stolonifera* L.), bermudagrass (*Cynodon* spp. Rich), turfgrass mixtures such as Dunes Mix [mixture of ‘Hardtop’ hard fescue (*F. brevipila* Tracey), ‘Baron’ Kentucky bluegrass, ‘Barok’ sheep fescue (*F. ovina* L.)] and Turf Sense [mixture of ‘Baronie’ Kentucky bluegrass, ‘Barlennium’ perennial ryegrass, and ‘Barcampsia’ tufted hairgrass [*Deschampsia cespitosa* (L.) P. Beauv.], and turfgrass blend like Turf Saver [blend of ‘Barlexas II’, ‘Barrington’, and ‘Labarinth’ tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] (Leinauer et al., 2010). Leinauer et al. (2010) also mentioned that the coating's ability to absorb and retain water can compensate for unfavorable conditions such as reduced irrigation and lower seeding rates, or a combination of both.



Figure 1.1. Coated turfgrass seeds (top) and respective noncoated turfgrass seed species counterparts underneath (bottom).

Seed coating technology could be used to deliver soil surfactants to establish golf course putting greens and sports field turf on hydrophobic sandy soils. Surfactant coatings had a positive impact on soil water content and tall fescue growth, specifically increasing its density, cover, and biomass under controlled environment in hydrophobic soils (Madsen et al., 2013). Further, coating seeds with a block copolymer containing nonionic alkyl and C1-C4 alkyl ethers of methyl oxirane-oxirane copolymers has been shown to be an effective approach for enhancing plant growth and seedling emergence in hydrophobic soils (Madsen et al., 2013, 2014, 2017). In another study, surfactant film coatings led to significant improvements in perennial ryegrass and tall fescue performance, resulting in up to a 47% increase in density, 48% in turf cover, and 46% in aboveground biomass for perennial ryegrass, and 22%, 23%, and 28% increases, respectively, for tall fescue compared with non-treated seeds (Madsen et al., 2016). These findings highlight the potential of surfactant seed coatings to improve germination and establishment under limited

irrigation conditions. McMillan et al. (2023) studied the impact of surfactant-coated and noncoated perennial ryegrass seeds across diverse substrates: 100% sand, 90% sand:10% peat (v/v), hydrophobic stearic acid-treated sand, and hydrophobic 90% sand:10% peat (v/v) in a controlled environment. Despite using half the amount of coated seeds compared with noncoated seeds due to the increased coating weight, the final turfgrass establishment in all substrates was either comparable or superior to that of noncoated seeds. Based on this study, soil surfactant coating presents a promising approach to enhance turfgrass establishment and improve soil-water dynamics, particularly in challenging conditions with limited precipitation (McMillan et al., 2023). Moran et al. (2025) evaluated a hydrophilic polymer (Hydroloc™) seed coating applied to perennial ryegrass and Kentucky bluegrass seed mixtures under field conditions. Coated Kentucky bluegrass seed increased fall groundcover by ~6% and significantly improved groundcover (2–4 weeks after sowing) under reduced soil moisture, with no differences observed thereafter. Similarly, Alvarez et al. (2014) reported strong species-dependent responses to polymer seed coatings (ASET 4000, 4001, and 4002) under saline irrigation, with reduced germination and establishment of perennial ryegrass but improved germination and 30-d establishment of the salt-tolerant seashore paspalum (*Paspalum vaginatum* Sw.). Other seed coating material, like biochar, has been evaluated in perennial grass and forb plants such as mountain brome (*Bromus marginatus* Nees ex Steud.), prairie junegrass [*Koeleria macrantha* (Ledeb.) Schult.], Wyeth buckwheat (*Eriogonum heracleoides* Nutt.) and western yarrow (*Achillea millefolium* L. var. *occidentalis* DC.) (Williams et al., 2016). In this study, biochar-coated seeds had a neutral or negative effect on the germination of these species in a controlled environment; however, they slightly improved root weight of the mountain brome and prairie junegrass cover in field studies. The effectiveness of seed coating may vary depending on the

specific plant species and environmental conditions, which adds complexity to this topic.

Activated carbon has also been used as a seed coating to potentially protect seeds from herbicidal effects on seedling emergence, plant growth, and development. Terry et al. (2021) suggested that combining carbon-coated seed with furrow treatments effectively reduces the detrimental effects of the mixture of pre-emergent herbicide containing the active ingredient imazapic and the post-emergent herbicide containing the active ingredient glyphosate on the establishment of bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Á. Löve). Plant growth regulators in seed coatings can accelerate, delay, or synchronize germination timing and promote root or shoot development, depending on the type and application. For example, Keefer et al. (2021) observed that the duration of sagebrush (*Artemisia* L. spp.) seed germination can be controlled using seed coating containing synthetic plant growth regulators. Past seed coating research on various plant species has shown that seed coating efficacy varies across species and environments; therefore, further research is needed to develop species- and environment-specific coatings that enhance germination, establishment, and stress tolerance.

Some coating materials are also used to improve abiotic stress resistance in grasses. Arslan and Qureshi (2022) demonstrated that bermudagrass seeds coated with biological preparations containing *Trichoderma harzianum* (i.e., suppresses plant pathogens), and soil bacteria, including *Bacillus subtilis* (i.e., growth-promoting activity), and *Bacillus megaterium* (i.e., ability to fix nitrogen), exhibited improved turfgrass quality, reduced leaf burn, and greater shoot and root biomass under drought stress. Compared with noncoated seeds, these microbial seed coatings partially mitigated drought-induced reductions in growth by improving nutrient availability and early root development, highlighting their potential as a complementary strategy to enhance turfgrass establishment and performance under drought-prone conditions.

Seed coating technology has progressed to incorporate a wide range of functional coating materials aimed to improve seed performance, especially under suboptimal conditions. While beneficial results have been reported for polymers, surfactants, biological agents, and growth regulators, the responses have varied widely because of differences among species and specific environmental conditions. Much of the existing research has focused on forage and other plant species, with relatively limited attention given to turfgrasses. With the increasing demand for sustainable turfgrass systems, especially amid growing water conservation efforts and focus on low-input conditions, further research is needed to optimize coating formulations tailored to turfgrass species. Moreover, future studies should also explore the potential of seed coatings to maintain seed viability and vigor during storage, thereby expanding their utility beyond field establishment to include long-term seed management strategies.

Effect of Seed Coating on Germination and Establishment

Seeding is the most common establishment method used for cool-season turfgrass species (Christians et al., 2017). Fast establishment vigor (i.e., seed germination and seedling growth) is essential for the successful establishment of turfgrass systems from seed (Braun et al., 2021, 2022; Madsen et al., 2016). The application of coatings on turfgrass seed has the potential to enhance establishment by reducing irrigation, seeding rates, or both (Leinauer et al., 2010); however, more research on coating types, species, and environmental conditions is needed.

Hathcock et al. (1984a) published the first greenhouse study on the use of coated turfgrass seed. Their research indicated that coating Kentucky bluegrass and tall fescue seeds with limestone using adhesives did not adversely affect seedling development. Subsequent greenhouse studies by Hathcock et al. (1984b) demonstrated that coated turfgrass seeds with fertilizers, including triple superphosphate (0-19.4-0) and dicalcium phosphate (0-8.8-0) for

phosphorus, urea (45-0-0) for nitrogen, sulfate of potash (0-0-41.5) for potassium, and ground dolomitic agricultural limestone (Calcium Carbonate Equivalent = 98.9%) for lime, could improve the germination and development of Kentucky bluegrass and tall fescue. Sochorec and Knot (2013) evaluated a fertilizer-based seed coating (iSeed®, containing fast-acting and slow-release fertilizers) under laboratory conditions using Chewings fescue ('Darwin') and slender creeping red fescue [*Festuca rubra* L. ssp. *littoralis* (G. Mey.) Auquier] ('Moccasin'), Kentucky bluegrass ('Yvette' and 'Miracle'), perennial ryegrass ('Beatrice' and 'Milan'), and white clover (*Trifolium repens* L. 'Pipolina' and 'Pirouette'). The iSeed treatment had no effect on final germination or shoot and root length for most turfgrass species; however, early germination of perennial ryegrass was initially delayed. In contrast, early germination increased in white clover, with the cultivar 'Pirouette' exhibiting significantly greater germination during the first 10 d compared with noncoated seed.

Some studies revealed that the use of fungicide-coated seeds resulted in a greater rate of successful growth and establishment in several plant species in field studies, including Kentucky bluegrass, perennial ryegrass, strong creeping red fescue (*Festuca rubra* L. ssp. *rubra* Gaudin), and two seed mixtures (Newell, 1997; Newell et al., 1999). Greipsson (1999) found that the establishment of Kentucky bluegrass on barren land in Iceland was significantly enhanced when seeds were coated with a combination of diatomaceous earth and cytokinin compared with noncoated seeds or diatomaceous-coated only seeds. This study supports Newell's previous findings (1997, 1999) by showing that applying a protective layer or coating to seeds can positively impact the growth and establishment of grass species, particularly Kentucky bluegrass. One reason Kentucky bluegrass may be more influenced by seed coating compared with other species is its known slow establishment vigor (Campbell et al., 2019). Layton et al. (2007)

examined the impact of seed coating on the germination of warm-season turfgrass, bermudagrass, seeded across six different temperature regimes in Mississippi, and their findings differed from those by Newell (1997, 1999) and Greipsson (1999). Layton et al. (2007) reported that coated-bermudagrass seeds did not increase germination rates compared with noncoated seeds when averaged across temperatures.

Serena et al. (2012b) found polymer-coated seeds delayed the early establishment (less than 50% cover) of turfgrass species such as Kentucky bluegrass, tall fescue, perennial ryegrass, bermudagrass, and seashore paspalum; however, coated-seeds had no significant effect on the number of estimated days to reach 95% coverage. Serena et al. (2012a) investigated the effect of ZEBA-coated seeds (superabsorbent cornstarch-based polymer) and reported increased germination rates of coated seashore paspalum and perennial ryegrass subjected to saline conditions compared with noncoated seeds in a laboratory study. Richardson and Hignight (2010) reported seed coatings combining fungicide and bio-stimulant, as well as ZEBA coatings, had a limited influence on the establishment of tall fescue and Kentucky bluegrass when investigated in a greenhouse. Munshaw et al. (2014) investigated various commercial seed coatings on the germination of five common bermudagrass cultivars including ‘Princess-77,’ ‘Riviera’ (46% CaCO_3 , fludioxonil, mefenoxam), ‘Transcontinental’ (CaCO_3 , zinc), ‘Yukon’ (45.5% CaCO_3 , 2.5% monocalcium phosphate, 2.0% calcium lignosulfonate) and ‘Arizona Common’. The authors reported that commercial seed coating did not influence the germination of common bermudagrass compared with noncoated seed.

Few studies have been conducted to investigate the effects of seed coatings under field conditions. Malinowski et al. (2012) studied the effects of Yellow Jacket® (Barenbrug) and supplemental irrigation on the seedling and aboveground biomass dry matter of summer-dormant

‘Proper’ tall fescue forage crop. This summer-dormant variety, which remains in a more dormant state during the hot summer months, showed potential to increase seedling dry matter, regardless of irrigation, and improved aboveground biomass dry matter, especially under conditions of limited soil moisture in Texas. Similarly, Pedrini et al. (2021) investigated the efficacy of salicylic acid as a seed coating to enhance the establishment of three grass species: speargrass [*Austrostipa scabra* (Lindl.) S.W.L. Jacobs & J. Everett], weeping grass [*Microlaena stipoides* (Labill.) R. Br.], and Knead Wallaby-grass (*Rytidosperma geniculatum* (J.M.Black) Connor & Edgar) in field conditions. Authors reported improved seedling survival and growth in grasses derived from coated seeds.

Multiple studies (Layton et al., 2007; Munshaw et al., 2014; Richardson & Hignight, 2010; Sochorec & Knot, 2013) have demonstrated no effect of seed coating on turfgrass establishment or a limited effect when using fertilizer-coated seeds or in greenhouse studies. On the contrary, others have reported enhanced seed germination and turfgrass establishment using various seed coatings (Greipsson, 1999; Hathcock et al., 1984a, 1984b; Leinauer et al., 2010; Newell, 1997; Newell et al., 1999; Serena et al., 2012a). These studies are summarized in Table 1.1. Overall, the results are conflicting regarding the use of seed coating technology to enhance turfgrass seed germination and establishment. Therefore, further research is necessary to a clearer understanding of the effect of different seed coating materials on the turfgrass establishment across various species.

Table 1.1. List of seed coating materials and their impact on germination and establishment of turfgrass and other grass and plant crops, listed chronologically within each crop section.

Crops	Species	Seed coating material	Treatment factors	Conditions	Summary of results	Reference
Turfgrass species	Kentucky bluegrass Tall fescue	Adhesives (to retain limestone seed coating)	Adhesives and species	Greenhouse	No negative effects of adhesives. Coatings on Kentucky bluegrass enhanced seedling growth but no effect was observed on tall fescue	Hathcock et al., 1984a
	Kentucky bluegrass Tall fescue	Fertilizers and limestone	Coating and species	Greenhouse	Limestone coating and some fertilizer coatings increased germination and seedling development	Hathcock et al., 1984b
	Kentucky bluegrass Perennial ryegrass Colonial bentgrass Strong creeping red fescue Seed mixture 1 (80% perennial ryegrass, 20% strong creeping red fescue) Seed mixture 2 (80% strong creeping red fescue, 20% colonial bentgrass)	Fungicide-coated seeds	Seed treatments and grass types/ mixtures	Field	Coated seeds increased ground cover and shoot density in Kentucky bluegrass, colonial bentgrass and seed mixture 2, but did not influence rooting depth. Coated seeds had minimal influence on perennial ryegrass or strong creeping red fescue.	Newell, 1997; Newell et al., 1999
	Kentucky bluegrass	Diatomaceous earth and cytokinin	Coating	Field	Significantly enhanced establishment compared with noncoated or diatomaceous earth-only coated seeds	Greipsson, 1999
	Tall fescue Kentucky bluegrass	Fungicide and bio stimulant, ZEBA-coating	Coating, species, and soil types	Greenhouse	Coated seeds had a minimal influence on overall establishment	Richardson & Hignight, 2010
	Creeping bentgrass Bermudagrass	ZEBA cornstarch polymer	Seeding rates, coating and	Field	Coated seeds exhibited enhanced turfgrass	Leinauer et al., 2010

Crops	Species	Seed coating material	Treatment factors	Conditions	Summary of results	Reference
	Dunes Mix (hard fescue, Kentucky bluegrass, sheep fescue) Turf Sense (Kentucky bluegrass, perennial ryegrass, tufted hairgrass) Turf Saver (three cultivars of tall fescue)		irrigation regimes		establishment at recommended and reduced seeding rates	
	Chewing fescue, Slender creeping red fescue Kentucky bluegrass (Yvette, Miracle) Perennial ryegrass (Beatrice, Milan) White clover (Pipolina, Pirouette)	Fertilizer-based coating (iSeed®)	Coating and species	Laboratory	Minimal effects overall; early germination of perennial ryegrass was delayed, while early germination increased in white clover (Pirouette)	Sochorec & Knot, 2013
	Kentucky bluegrass Tall fescue Perennial ryegrass Bermudagrass Seashore paspalum	ZEBA-coating	Coating, salinity levels and media	Laboratory (saline conditions)	Coated seeds increased germination rates compared with noncoated seeds (dependent on the medium)	Serena et al., 2012a
	Kentucky bluegrass Tall fescue Perennial ryegrass Bermudagrass Seashore paspalum	Polymer-coated seeds	Salinity levels and irrigation treatments	Field	Coated seeds delayed early establishment (<50% cover); no effect on days to reach 95% coverage	Serena et al., 2012b
	Tall fescue	Surfactant- alkyl-terminated ethylene oxide-propylene oxide block copolymer surfactant	Surfactant coatings rates and soil types	Controlled environment	Coated seeds enhanced plant growth and seedling emergence in hydrophobic soils. Coated seeds improved soil water content, increased turfgrass density, cover, and biomass	Madsen et al., 2013

Crops	Species	Seed coating material	Treatment factors	Conditions	Summary of results	Reference
	Bermudagrass cultivars (Princess-77, Riviera, Transcontinental, Yukon, Arizona Common)	Various commercial seed coatings	Coating, cultivars and temperature regimes	Controlled environment (germination chamber)	Coated seeds had no influence on germination	Layton et al., 2007; Munshaw et al., 2014
	Perennial ryegrass Seashore paspalum	Polymer seed coating	Coating, Saline irrigation levels	Controlled environment	Coated seed reduced germination and slowed establishment of perennial ryegrass under salinity, whereas germination and 30-d establishment of seashore paspalum were improved	Alvarez et al., (2014)
	Perennial ryegrass Tall fescue	Surfactant film coating	Coating and temperatures	Controlled environment (growth chamber)	Coated seeds increased germination speed but did not influence final germination percentage. Coated seeds exhibited higher density, cover, and aboveground biomass, especially in perennial ryegrass.	Madsen et al., 2016
	Bermudagrass	Biological preparations containing <i>Trichoderma harzianum</i> , <i>Bacillus subtilis</i> , and <i>Bacillus megaterium</i>	Coating, growing media and irrigation regimes	Field	Some coatings help mitigate the effects of drought stress	Arslan and Qureshi, 2022
	Perennial ryegrass	Surfactant coating	Substrates and coating	Controlled environment (greenhouse)	Higher volumetric water content in surfactant-coated seed root zones, enhances stand establishment, effective in	McMillian et al., 2023

Crops	Species	Seed coating material	Treatment factors	Conditions	Summary of results	Reference
					challenging conditions with limited precipitation	
	Perennial ryegrass/Kentucky bluegrass seed mixtures	Hydrophilic polymer (Hydroloc™)	Coating, seed mixtures and seeding rates	Field	Coated seed increased Kentucky bluegrass fall groundcover by ~6%; however, effects were not sustained beyond 4 weeks.	Moran et al., 2025
Other grasses and plants	Summer-dormant ‘Proper’ tall fescue forage crop	Yellow Jacket® seed coating	Supplemental irrigation	Field	Coated seed increased seedling dry matter and aboveground biomass dry matter, especially under limited soil moisture conditions	Malinowski et al., 2012
	Mountain brome Prairie junegrass Wyeth's buckwheat Western yarrow	Biochar	Coating thickness and environmental conditions	Controlled environment Field	Neutral or negative effect of coating on germination Coating slightly improved the root weight of mountain brome and cover in prairie junegrass	Williams et al., 2016
	Bluebunch wheatgrass	Activated carbon	Coating, Furrow treatments	Field	Coating and furrow treatments reduced the detrimental effects of herbicides on seedling establishment.	Terry et al., 2021
	Big sagebrush Low sagebrush	Synthetic plant growth regulators (PGRs)	Species, coating and temperature	Controlled environment	Germination timing can be controlled by using artificial PGRs as seed coatings	Keefer et al., 2021
	Speargrass Weeping grass, Kneed Wallaby-grass	Salicylic acid	Seedling survival and growth	Field	Coated seed improved seedling survival and growth	Pedrini et al., 2021

Seed Viability and Longevity

The ability of seeds to retain viability during storage and germinate consistently at sowing is essential for establishing turfgrass stands. The germination process involves the seed undergoing imbibition, taking in water and nutrients from the surrounding soil, which then triggers enzymatic reactions to initiate the growth and development of the embryonic plant inside (Ali & Elozeiri, 2017). This process is essential for the success of a turfgrass stand because it determines the strength and competitiveness of the desired turfgrass species against other germinating plant species (i.e., weed species) in the soil (Harper, 1961; Ross & Harper, 1972). Among the numerous factors affecting seed germination and viability storage condition and duration are considered most critical (De Vitis et al., 2020; Gebeyehu, 2020). Extended storage durations contribute to the decline in cellular and metabolic integrity in seeds and seedlings (Kranner, 2013). This deterioration can be attributed to oxidative processes (Walters et al., 2010), resulting in the degradation of enzymes (Goel et al., 2003), lipids impacting cellular membranes (Harman & Mattick, 1976), and damage to DNA (El-Maarouf-Bouteau et al., 2011) and RNA (Fleming et al., 2019). The viability of seeds can be negatively impacted by duration of seed storage, with a proportional reduction in seed viability as storage time increases (Bortey et al., 2016). Therefore, the seeds must be stored properly so that the seeds would have optimal viability when they are sown. The process of decreasing seed viability cannot be stopped but might be able to be delayed to attain a longer shelf life (i.e., longevity) (Faisal, 2019). Seed longevity refers to the duration for which seeds can be preserved and maintain their ability to germinate, provided they are stored under specific conditions. The longevity of seeds can vary depending on the species and the storage conditions (De Vitis et al., 2020). The deterioration of seed longevity during storage can be influenced by various physical, chemical, and

environmental factors (Walters et al., 2010). Among the various factors, environmental conditions such as moisture and temperature play a key role in limiting seed lifespan and overall longevity.

Seed coating technology is increasingly implemented to enhance seed germination and viability (Pedrini et al., 2017); yet its potential effects on turfgrass seed storage remain unknown, despite the growing commercial availability of coated turfgrass seed. Numerous studies in the past have investigated the influence of various storage conditions and durations on seed germination, viability, and longevity (Table 1.2). Proper storage conditions are essential for maintaining seed germination and vigor over time. Enhancing the ability to store seeds involves precisely managing the storage environment, with specific focus on controlling temperature and relative humidity within storage areas (Welty et al., 1987). Vertucci and Roos (1990) proposed that maintaining leguminous crops [peanut (*Arachis hypogaea* L.); soybean, pea (*Pisum sativum* L.)], oilseed crop [sunflower (*Helianthus annuus* L.)] and vegetable lettuce seeds at a relative humidity range of 19% to 27% is optimal for preserving their longevity during storage for periods ranging from 2 to 9 months. According to Ackigoz and Knowles (1983), temperature is a major factor influencing seed viability, inversely related to storage temperature. Knowles (1983) found 80-90% seed viability of crested wheatgrass (*Agropyron cristatum* L. Gaertn.), intermediate wheatgrass (*Agropyron intermedium* Host. Beauv.), and smooth brome grass (*Bromus inermis* Leyss.) stored at ~20 and 0°F after 20 years of storage. They also mentioned drying seeds for 7.5 h at 140°F before storing seed can maintain the seed viability over non-dried seeds, which suggests seed moisture during storage is important. Similarly, Bass and Stanwood (1978) also reported good viability of sorghum seed (*Sorghum bicolor* L. Moench.) stored for 16 years at ~30 and 10°F, regardless of seed moisture content, and atmospheric environment of the

storage medium. Rincker and Maguire (1979) and Rincker (1981) found similar or better germination for orchard grass, smooth brome grass, timothy (*Phleum pratense* L.) stored for 14 years at 5°F and 60% relative humidity compared with the fresh seeds. These studies highlight the critical role of temperature and humidity management while storage in maintaining seed viability and longevity across various plant species, with specific outcomes varying by species.

Research has demonstrated that maintaining optimal storage conditions is equally crucial in turfgrass species. Several studies have been conducted to evaluate pre-sowing treatments, various storage conditions, and durations to ensure the quality, viability, and successful establishment of turfgrass seeds. Sprague (1940) found that exposing moistened seeds (pre-seed treatment) of Kentucky bluegrass and orchard grass to temperatures between 41 and 59°F for a duration of 10 to 14 days led to 90% germination, indicating that controlled temperature and pre-seed treatment can significantly influence seed germination. Rincker (1986) explored the impact of storage conditions on Kentucky bluegrass, red fescue, chewings fescue and orchard grass. The study revealed that germination percentages in these grasses remained close to original levels for a minimum of 8 years when subjected to continuous freezing at temperatures most frequently near 5°F, or freezing with weekly thawing for 24 hours followed by return to subfreezing storage at temperatures between 23 and 5°F. Though, a significant decline in germination occurs when stored in an unheated warehouse (-4 to 104°F) (Rincker, 1986). Nutile (1964) reported that the seed viability of Kentucky bluegrass and red fescue declined significantly at 73 to 86°F with a moisture content of 0.4–1% after five years of storage, particularly while *Agrostis* spp. L. maintained viability even at 0.3 to 0.4%, and viability loss was minimized when seeds were stored at ~45°F instead of room temperature. Marshall and Lewis (2004) found reduced emergence rates and seedling counts of perennial ryegrass, Italian ryegrass (*Lolium multiflorum*

Lam.), hybrid ryegrass (*Lolium × boucheanum* Kunth.), and white clover (*Trifolium repens* L.) after 12 years of storage in a refrigerator (39°F without humidity control) compared with storage in a controlled environment seed storage maintained at 36°F temperature and 10 to 20% relative humidity. Bukvić et al. (2015) reported that perennial ryegrass seeds stored at -112°F for 9 months had the highest germination speed, germination percentage, and plumule length, compared with storage at room temperature (70°F); however, these traits declined with longer storage periods up to 30 months. Qian et al. (2000) observed zoysiagrass (*Zoysia japonica* Steud.) seed germination percentage declined from 97% to 40% over 5 years in a seed storeroom maintained at 59 to 86°F; however, storage in sealed polyethylene bags at a lower temperature (41°F) demonstrated the ability to slow down seed deterioration. Moreover, Mao et al. (2009) proposed that zoysiagrass seed can maintain a higher vigor level when harvested in the field at the hard seed stage, and then kept at low temperature (45°F) for a year or less. These studies reinforce the critical role of storage management in preserving seed viability, vigor, and successful germination across both crop and turfgrass species.

All these studies have focused on seed storage conditions and durations, with no research specifically investigating the impact of seed coatings on seed storage and longevity in turfgrass. While seed coatings have been shown to benefit turfgrass establishment under suboptimal conditions (Leinauer et al., 2010; Serena et al., 2012a), further research is needed to explore their potential for extending storage duration and improving seed storage practices. Investigating the influence of seed coatings on storage longevity will provide valuable insights for optimizing turfgrass seed management and ensuring successful establishment.

Table 1.2. Overview of seed storage studies: Effects on seed germination and viability of turfgrass and other grass and plant crops, listed chronologically within each crop species.

Crops	Species	Storage duration	Factors	Conditions	Results	Reference
Turfgrass Species	Kentucky bluegrass Orchard grass	-	Pre-seed treatment and temperature	Controlled environment	90% germination achieved after seed pre-treatment at 41–59°F for 10–14 days	Sprague, 1940
	Kentucky bluegrass Red fescue, <i>Agrostis</i> spp.	5 years	Storage temperature and moisture content	Controlled environment	Seed viability of Kentucky bluegrass and red fescue declined after 5 years at room temperature; <i>Agrostis</i> spp. maintained the viability and viability loss reduced when stored at 44.6°F.	Nutile, 1964
	Kentucky bluegrass Red fescue, Chewings fescue Orchard grass	8 years	Storage conditions: freezing and thawing cycles	Laboratory	Germination maintained for ≥8 years under freezing and declined under unheated warehouse (-4 to 104°F)	Rincker, 1986
	Zoysiagrass	5 years	Storage temperature and packaging	Controlled environment	Germination percentage declined from 96.5% to 40.5% over 5 years at 59-86°F; slowed deterioration at 41°F in sealed polyethylene bags	Qian et al., 2000
	Zoysiagrass	6 to 18 months	Storage temperature and harvest stage	Controlled environment	Higher vigor when harvested at hard seed stage and stored at 44.6°F for ≤1 year	Mao et al., 2009
	Perennial ryegrass	9 to 30 months	Storage temperature and duration	Controlled environment	Highest germination speed, percentage, and seedling plumule length storing at -112°F for 9 months; reduced seed performance with longer storage and least favorable at 69.8°F	Bukvić et al., 2015
Other grasses and plants	Sorghum	16 years	Moisture levels, atmospheric conditions, and	Controlled environment	Good viability after 16 years at 30.2°F and 10.4°F, regardless of	Bass & Stanwood, 1978

		temperature regimes	seed moisture content and atmospheric conditions			
Orchard grass Smooth brome grass Timothy Meadow fescue	12 to 15 years	Storage conditions, temperature and relative humidity	-	Germination varied across various grasses	Rincker & Maguire, 1979; Rincker, 1981	
Crested wheatgrass Intermediate wheatgrass Smooth brome grass	20 years	Storage conditions, temperature and duration	Controlled environment	80-90% seed viability after 20 years at 19.4 and 0°F temperature; improved with seed drying before storage	Knowles, 1983	
Field crops: Peanut Soybean Pea Sunflower Lettuce	2 to 9 months	Storage duration and relative humidity	Controlled environment	Optimal relative humidity for preserving longevity: 19%-27% for 2-9 months	Vertucci & Roos, 1990	
Perennial ryegrass Italian ryegrass Hybrid ryegrass White clover	12 years	Storage conditions and multiple grass species	Controlled and field conditions	Reduced emergence rate and seedling count when stored in refrigerator for 12 years compared with controlled environment seed store	Marshall & Lewis, 2004	

Conclusions and Future Prospects

A review of literature on seed coatings and turfgrass establishment informs mixed outcomes, with some studies showing potential benefits of seed coating in enhancing germination and establishment of turfgrasses, while others indicate minimal to no effects. Further research is needed to address this variability in results. The effectiveness of seed coating may depend on several factors, including the seed-coating material type, turfgrass species, and environmental conditions. Additional studies should be conducted to draw stronger conclusions and consider the wide range of variables and parameters mentioned in this review. Future investigations should also focus on optimizing seed coatings and assessing potential interactions between seed coatings and various abiotic and biotic stresses. Additionally, multiple turfgrass species should be investigated, particularly those with varying establishment vigor rates. Moreover, it is crucial to examine the effects of storage conditions and duration on turfgrass seed viability and longevity when using seed-coating technology. Overall, further research is needed to deepen the understanding of seed coating technology in turfgrass systems, possibly promoting more efficient and sustainable storage and establishment practices in the future. Further investigation will help identify the most effective seed-coating approaches and application strategies to improve turfgrass establishment in diverse environmental conditions. Currently, turfgrass practitioners should be hesitant to use coated turfgrass seed due to its inconsistent performance. More research on seed coating will provide more sound recommendations to turfgrass practitioners.

References

- Accinelli, C., Abbas, H. K., Little, N. S., Kotowicz, J. K., Mencarelli, M., & Shier, W. T. (2016). A liquid bioplastic formulation for film coating of agronomic seeds. *Crop Protection*, 89, 123–128. <https://doi.org/10.1016/j.cropro.2016.07.010>
- Ackigoz, E., & Knowles, R. P. (1983). Long-term storage of grass seeds. *Canadian Journal of Plant Science*, 63, 669–674. <https://doi.org/10.4141/cjps83-084>
- Agake, S. I., Artigas Ramirez, M. D., Kojima, K., Ookawa, T., Ohkama-Ohtsu, N., & Yokoyama, T. (2021). Seed coating by biofertilizer containing spores of *Bacillus pumilus* TUAT1 strain enhanced initial growth of *Oryza sativa* L. *Agronomy Journal*, 113, 3708–3717. <https://doi.org/10.1002/agi2.20747>
- Ali, A. S., & Elozeiri, A. A. (2017). Metabolic processes during seed germination. *Advances in Seed Biology*, 2017, 141–166. <https://www.intechopen.com/chapters/56975>
- Alvarez, G., Leinauer, B., Sevostianova, E., Serena, M., & Pornaro, C. (2014). Effects of experimental polymer seed coating on germination and establishment of perennial ryegrass and seashore paspalum under saline irrigation. *European Journal of Turfgrass Science*, 27-28.
- Arslan, M., & Qureshi, M. (2022). Response of bermudagrass grown in different soil media to drought stress. *Turkish Journal of Range and Forage Science*, 3, 18–24. <https://doi.org/10.51801/turkjrf.1077960>
- Avelar, S. A. G., Sousa, F. V. D., Fiss, G., Baudet, L., & Peske, S. T. (2012). The use of film coating on the performance of treated corn seed. *Revista Brasileira de Sementes*, 34, 186–192. <https://doi.org/10.1590/S0101-31222012000200001>
- Bashan, Y., Hernandez, J. P., Leyva, L. A., & Bacilio, M. (2002). Alginate microbeads as inoculant carriers for plant growth-promoting bacteria. *Biology and Fertility of Soils*, 35, 359–368. <https://doi.org/10.1007/s00374-002-0481-5>
- Bass, L. N., & Stanwood, P. C. (1978). Long-term preservation of sorghum seed as affected by seed moisture, temperature, and atmospheric environment. *Crop Science*, 18, 575–577. <https://doi.org/10.2135/cropsci1978.0011183X001800040012x>
- Bortey, H. M., Sadia, A. O., & Asibuo, J. Y. (2016). Effect of seed storage period and temperature upon seed and seedling traits of perennial ryegrass (*Lolium perenne* L.). *Polopojerida*, 21, 3–9.
- Braun, R. C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022). Review of cool-season turfgrass water use and requirements: II. Responses to drought stress. *Crop Science*, 62, 1685–1701. <https://doi.org/10.1002/csc2.20790>

- Braun, R. C., Mandal, P., Nwachukwu, E., & Stanton, A. (2024). The role of turfgrasses in environmental protection and their benefits to humans: thirty years later. *Crop Science*, 64, 2909–2944. <https://doi.org/10.1002/csc2.21383>
- Braun, R. C., Straw, C. M., Soldat, D. J., Bekken, M. A. H., Patton, A. J., Lonsdorf, E. V., & Horgan, B. P. (2023). Strategies for reducing inputs and emissions in turfgrass systems. *Crop, Forage and Turfgrass Management*, 9, e20218. <https://doi.org/10.1002/cft2.20218>
- Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2021). Investigation of cool-season species, seeding rate, and nitrogen fertilization in sod production: I. Establishment and sod tensile strength. *Agronomy Journal*, 113, 4176–4189. <https://doi.org/10.1002/agi2.20810>
- Brown, V. S., Erickson, T. E., Merritt, D. J., Madsen, M. D., Hobbs, R. J., & Ritchie, A. L. (2021). A global review of seed enhancement technology use to inform improved applications in restoration. *Science of the Total Environment*, 798, 149096. <https://doi.org/10.1016/j.scitotenv.2021.149096>
- Bukvić, G., Gantner, R., Grljušić, S., Popović, B., Agić, D., & Stanisavljević, A. (2015). Effects of storage period and temperature upon seed and seedling traits of perennial ryegrass (*Lolium perenne* L.). *Poljoprivreda*, 21, 3–9. <https://doi.org/10.18047/poljo.21.2.1>
- Campaña, J. M., & Arias, M. (2020). Nanofibers as a delivery system for arbuscular mycorrhizal fungi. *ACS Applied Polymer Materials*, 2, 5033–5038. <https://doi.org/10.1021/acsapm.0c00874>
- Campbell, J. H., Henderson, J. J., Inguagiato, J. C., Wallace, V. H., & Minniti, A. (2019). Optimizing pre-germination techniques for Kentucky bluegrass and perennial ryegrass. *Journal of Environmental Horticulture*, 37, 19–23. <https://doi.org/10.24266/0738-2898-37.1.19>
- Chandrika, K. P., Prasad, R. D., & Godbole, V. (2019). Development of chitosan-PEG blended films using *Trichoderma*: Enhancement of antimicrobial activity and seed quality. *International Journal of Biological Macromolecules*, 126, 282–290. <https://doi.org/10.1016/j.ijbiomac.2018.12.208>
- Christians, N. E., Patton, A. J., & Law, Q. D. (2017). *Fundamentals of Turfgrass Management* (5th ed). Hoboken, NJ: John Wiley & Sons, Inc.
- Cortés-Rojas, D., Beltrán-Acosta, C., Zapata-Narvaez, Y., Chaparro, M., Gómez, M., & Cruz-Barrera, M. (2021). Seed coating as a delivery system for the endophyte *Trichoderma koningiopsis* Th003 in rice (*Oryza sativa*). *Applied Microbiology and Biotechnology*, 105, 1889–1904. <https://doi.org/10.1007/s00253-021-11146-9>
- De Gregorio, P. R., Michavila, G., Ricciardi Muller, L., de Souza Borges, C., Pomares, M. F., Saccol de Sá, E. L., ... & Vincent, P. A. (2017). Beneficial rhizobacteria immobilized in

- nanofibers for potential application as soybean seed bioinoculants. *Plos one*, 12, e0176930. <https://doi.org/10.1371/journal.pone.0176930>
- De Vitis, M., Hay, F. R., Dickie, J. B., Trivedi, C., Choi, J., & Fiegner, R. (2020). Seed storage: maintaining seed viability and vigor for restoration use. *Restoration Ecology*, 28, S249–S255. <https://doi.org/10.1111/rec.13174>
- El-Maarouf-Bouteau, H., Mazuy, C., Corbineau, F., & Bailly, C. (2011). DNA alteration and programmed cell death during ageing of sunflower seed. *Journal of Experimental Botany*, 62, 5003–5011. <https://doi.org/10.1093/jxb/err198>
- Faisal, M., Ahmad, U., & Wulandani, D. (2019). Determination of mung bean seed viability change in vacuum packaging during storage in different temperatures. In *IOP Conference Series: Materials Science and Engineering*, 557, 012074.
- Fleming, M. B., Hill, L. M., & Walters, C. (2019). The kinetics of ageing in dry-stored seeds: a comparison of viability loss and RNA degradation in unique legacy seed collections. *Annals of Botany*, 123, 1133–1146. <https://doi.org/10.1093/aob/mcy217>
- Gebeyehu, B. (2020). Review on: Effect of seed storage period and storage environment on seed quality. *International Journal of Applied Agricultural Sciences*, 6, 185–190. <https://doi.org/10.11648/J.IJAAS.20200606.14>
- Giordano, N., Hayes, D., Hefley, T. J., Lacasa, J., Beres, B. L., Haag, L. A., & Lollato, R. P. (2025). A Bayesian framework to model variance of grain yield response to plant density. *Plant Methods*, 21, 38. <https://doi.org/10.1186/s13007-025-01355-y>
- Goel, A., Goel, A. K., & Sheoran, I. S. (2003). Changes in oxidative stress enzymes during artificial ageing in cotton (*Gossypium hirsutum* L.) seeds. *Journal of Plant Physiology*, 160, 1093–1100. <https://doi.org/10.1078/0176-1617-00881>
- Gomes, L. C. A., Júnior, J. L. D. A. M., Melo, L. D. F. D. A., & Lins, A. P. D. N. P. (2025). Coating of corn seeds: scientific advances and global collaborations towards agricultural sustainability. *Discover Sustainability*, 6, 222. <https://doi.org/10.1007/s43621-025-01067-2>
- Greipsson, S. (1999). Seed coating improves the establishment of surface seeded *Poa pratensis* used in revegetation. *Seed Science and Technology*, 27, 1029–1032.
- Halmer, P. (2000). Commercial seed treatment technology. *Seed Technology and its Biological Basis*. Sheffield Academic Press, Sheffield, England, 257–286.
- Halmer, P. (2008). Seed Technology and Seed Enhancement. *Acta Horticulturae*, 771, 17–26. <https://doi.org/10.17660/ActaHortic.2008.771.1>
- Harman, G. E., & Mattick, L. R. (1976). Association of lipid oxidation with seed ageing and death. *Nature*, 260, 323–324. <https://doi.org/10.1038/260323a0>

- Harper, J. L. (1961). Approaches to the study of plant competition. In F. L. Milthorpe (Ed.), *Mechanisms in biological competition*, Cambridge, U.K.: Cambridge University Press, 1–39.
- Hathcock, A. L., Dernoeden, P. H., Murray, J. J., & Wehner, D. J. (1984a). Seed germination of tall fescue and Kentucky bluegrass as affected by adhesives. *HortScience*, 19, 442–443. <https://doi.org/10.21273/HORTSCI.19.3.442>
- Hathcock, A. L., Dernoeden, P. H., Turner, T. R., & McIntosh, M. S. (1984b). Tall fescue and Kentucky bluegrass response to fertilizer and lime seed coatings. *Agronomy Journal*, 76, 879–883. <https://doi.org/10.2134/agronj1984.00021962007600060005x>
- Hill, H. J. (1999). Recent developments in seed technology. *Journal of New seeds*, 1, 105–112.
- Jeffs, K. A. (1986) *Seed Treatment*, 2nd ed.; The British Crop Protection Council (BCPC) Publication: Surrey, UK, 332.
- Jiang, Y., & Su, D. (2018). Models of turfgrass seed germination related to water content. *Plos One*, 13, e0204983. <https://doi.org/10.1371/journal.pone.0204983>
- Kaufman, G. (1991). Seed coating: A tool for stand establishment; a stimulus to seed quality. *HortTechnology*, 1, 98–102. <https://doi.org/10.21273/horttech.1.1.98>
- Keefer, C. E., Clair, S. B. S., Radke, J., Allen, P. S., Hoose, B. W., Fahning, S., ... & Madsen, M. D. (2021). Use of plant growth regulators to expand sagebrush germination rates for restoration efforts. *Rangeland Ecology & Management*, 76, 48–55. <https://doi.org/10.1016/j.rama.2021.01.009>
- Knowles, R. (1983). Long-term storage of grass seeds.
- Kranner, I. (2013). Mechanisms of seed ageing. *South African Journal of Botany*, 86, 140–140. <https://doi.org/10.1016/j.sajb.2013.02.010>
- Layton, J., Munshaw, G., Stewart, B., Baldwin, B., & Philley, H. (2007). Does seed coating affect bermudagrass germination? *ASA-CSSA-SSSA Annual Meeting Abstracts*. ASA, CSSA, and SSSA, Madison, WI.
- Leinauer, B., Serena, M., & Singh, D. (2010). Seed coating and seeding rate effects on turfgrass germination and establishment. *HortTechnology*, 20, 179–185. <https://doi.org/10.21273/horttech.20.1.179>
- Ma, Y. (2019). Seed coating with beneficial microorganisms for precision agriculture. *Biotechnology Advances*, 37, 107423. <https://doi.org/10.1016/j.biotechadv.2019.107423>
- Madsen, M. D., Fidanza, M. A., Barney, N. S., Kostka, S. J., Badrakh, T., & McMillan, M. F. (2016). Low-dose application of nonionic alkyl terminated block copolymer surfactant enhances turfgrass seed germination and plant growth. *HortTechnology*, 26, 379–385. <https://doi.org/10.21273/horttech.26.4.379>

- Madsen, M. D., Kostka, S. J., Hulet, A., Mackey, B. E., Harrison, M. A., & McMillan, M. F. (2013). Surfactant seed coating—a strategy to improve turfgrass establishment on water repellent soils. *In International Symposium on Adjuvants for Agrochemicals*, 205–210.
- Madsen, M. D., Petersen, S. L., & Taylor, A. G. (2017). Seed coating compositions and methods for applying soil surfactants to water-repellent soil. *Pub. No. WO/2010/111309. International Application No. PCT/US2010/28371.*
- Madsen, M. D., Zvirzdin, D. L., Roundy, B. A., & Kostka, S. J. (2014). Improving reseeding success after catastrophic wildfire with surfactant seed coating technology. *Pesticide Formulation and Delivery Systems*, 33, 44–48. <https://doi.org/10.1520/STP156920120181>
- Malinowski, D. P., Emendack, Y. Y., & Singh, D. (2012). Yellow Jacket seed coating improves establishment of ‘Prosper’ summer-dormant tall fescue. *Forage & Grazinglands*, 10, 1–13. <https://doi.org/10.1094/FG-2012-1113-01-RS>
- Mao, P. S., Wang, X. G., Wang, Y. H., & Han, J. G. (2009). Effect of storage temperature and duration on the vigor of zoysiagrass (*Zoysia japonica* Steud.) seed harvested at different maturity stages. *Grassland Science*, 55, 1–5. <https://doi.org/10.1111/j.1744-697X.2009.00129.x>
- Markets & Markets. (2025). Seed coating market by additive type (polymers, colorants, binders, minerals/pumice, active ingredients), crop type, process (film coating, pelleting, encrusting), coating type (bio-based, synthetic), form, and region – Global forecast to 2030. Report Code: AGI 2751. <https://www.marketsandmarkets.com> (accessed 10 July 2025).
- Marshall, A. H., & Lewis, D. N. (2004). Influence of seed storage conditions on seedling emergence, seedling growth and dry matter production of temperate forage grasses. *Seed Science and Technology*, 32, 493–501. <https://doi.org/10.15258/sst.2004.32.2.19>
- McMillan, M., Daroub, S., Moore, K., Erickson, J., Kostka, S., & Fidanza, M. (2023). Surfactant-coated seed emergence and establishment under deficit irrigation in hydrophilic and hydrophobic soils. *Journal of Environmental Horticulture*, 41, 33–39. <https://doi.org/10.24266/2573-5586-41.1.33>
- Moran, J., Goggi, A. S., Moore, K. J., Fei, S. Z., & Gruss, S. (2025). Improving groundcover establishment through seed rate, seed ratio, and hydrophilic seed coating. *Agronomy*, 15, 1927. <https://doi.org/10.3390/agronomy15081927>
- Munshaw, G. C., Layton, J. M., Stewart, B. R., Philley, H. W., Beasley, J. S., & Lemus, R. W. (2014). The Germination responses of five bermudagrass cultivars to seed coating and temperature. *HortScience*, 49, 1225–1229. <https://doi.org/10.21273/HORTSCI.49.9.1225>
- Newell, A. J. (1997). Effect of different seed treatments and coatings on the germination and establishment of four grass species. *Journal of Turfgrass Science*, 73, 67–72.

- Newell, A. J., Hart-Woods, J. C., & Crossley, F. M. (1999). Investigation of the effects of Fortiva seed treatment on the establishment of different grass species and mixtures. *Journal of Turfgrass Science*, 75, 89–99.
- Nutile, G. E. (1964). Effect of desiccation on viability of seeds.
- Pedrini, S., Balestrazzi, A., Madsen, M. D., Bhalsing, K., Hardegree, S. P., Dixon, K. W., & Kildisheva, O. A. (2020). Seed enhancement: getting seeds restoration-ready. *Restoration Ecology*, 28, S266–S275. <https://doi.org/10.1111/rec.13184>
- Pedrini, S., Merritt, D. J., Stevens, J., & Dixon, K. (2017). Seed coating: Science or marketing spin?. *Trends in Plant Science*, 22, 106–116. <https://doi.org/10.1016/j.tplants.2016.11.002>
- Pedrini, S., Stevens, J. C., & Dixon, K. W. (2021). Seed encrusting with salicylic acid: a novel approach to improve establishment of grass species in ecological restoration. *Plos One*, 16, e0242035. <https://doi.org/10.1371/journal.pone.0242035>
- Pinto, J. G. C. P., Munaro, L. B., Jaenisch, B. R., Nagaoka, A. K., & Lollato, R. P. (2019). Wheat variety response to seed cleaning and treatment after Fusarium head blight infection. *Agrosystems, Geosciences & Environment*, 2, 1–8. <https://doi.org/10.2134/age2019.05.0034>
- Qian, J. Z., Han, J. G., Ni, X. Q., Song, J. F. (2000). A study on physiological and biochemical changes in storing zoysia seed. *Acta Agrestia Sinica*, 3, 177–185.
- Richardson, M. D., & Hignight, K. W. (2010). Seedling emergence of tall fescue and Kentucky bluegrass, as affected by two seed coating techniques. *HortTechnology*, 20, 415–417. <https://doi.org/10.21273/HORTTECH.20.2.415>
- Rincker, C. M. (1981). Long-Term Subfreezing Storage of Forage Crop Seeds. *Crop Science*, 21, 424–427. <https://doi.org/10.2135/cropsci1981.0011183X002100030017x>
- Rincker, C. M. (1986). Germination of grass seeds after 8 years of weekly removal from subfreezing storage. *Crop Science*, 26, 165–166. <https://doi.org/10.2135/cropsci1986.0011183X002600010039x>
- Rincker, C. M., & Maguire, J. D. (1979). Effect of seed storage on germination and forage production of seven grass cultivars. *Crop Science*, 19, 857–860. <https://doi.org/10.2135/cropsci1979.0011183X001900060027xa>
- Ross, M. A., & Harper, J. L. (1972). Occupation of biological space during seedling establishment. *Journal of Ecology*, 60, 77–88. <https://doi.org/10.2307/2258041>
- Scott, J. M. (1989). Seed coatings and treatments and their effects on plant establishment. *Advances in Agronomy*, 42, 43–83. [https://doi.org/10.1016/S0065-2113\(08\)60523-4](https://doi.org/10.1016/S0065-2113(08)60523-4)

- Serena, M., Leinauer, B., Sallenave, R., Schiavon, M., & Maier, B. (2012a). Media selection and seed coating influence germination of turfgrasses under salinity. *HortScience*, 47, 116–120. <https://doi.org/10.21273/HORTSCI.47.1.116>
- Serena, M., Leinauer, B., Sallenave, R., Schiavon, M., & Maier, B. (2012b). Turfgrass establishment from polymer-coated seed under saline irrigation. *Hort Science*, 47, 1789–1794. <https://doi.org/10.21273/HORTSCI.47.12.1789>
- Sochorec, M., & Knot, P. (2013). The effect of fertilizer seed coating on the germinating capacity and initial development of some turf grass species and white clover. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 60, 23.
- Sprague, V. G. (1940). Germination of freshly harvested seeds of several *Poa* species and of *Dactylis glomerata*.
- Svejcar, L. N., Brown, V. S., Ritchie, A. L., Davies, K. W., & Svejcar, T. J. (2022). A new perspective and approach to ecosystem restoration: a seed enhancement technology guide and case study. *Restoration Ecology*, 30. <https://doi.org/10.1111/rec.13615>
- Taylor, A. G., & Harman, G. E. (1990). Concepts and technologies of selected seed treatments. *Annual Review of Phytopathology*, 28, 321–339. <https://doi.org/10.1146/annurev.py.28.090190.001541>
- Terry, T. J., Madsen, M. D., Gill, R. A., Anderson, V. J., & St. Clair, S. B. (2021). Selective herbicide control: using furrows and carbon seed coatings to establish a native bunchgrass while reducing cheatgrass cover. *Restoration Ecology*, 29, e13351. <https://doi.org/10.1111/rec.13351>
- Vertucci, C. W., & Roos, E. E. (1990). Theoretical basis of protocols for seed storage. *Plant Physiology*, 94, 1019–1023. <https://doi.org/10.1104/pp.94.3.1019>
- Walters, C., Ballesteros, D., & Vertucci, V. A. (2010). Structural mechanics of seed deterioration: standing the test of time. *Plant Science*, 179, 565–573. <https://doi.org/10.1016/j.plantsci.2010.06.016>
- Welty, R. E., Azevedo, M. D., & Cooper, T. M. (1987). Influence of moisture content, temperature, and length of storage on seed germination and survival of endophytic fungi in seeds of tall fescue and perennial ryegrass. *Phytopathology*, 77, 893–900. <https://doi.org/10.1094/Phyto-77-893>
- Williams, M. I., Dumroese, R. K., Page-Dumroese, D. S., & Hardegree, S. P. (2016). Can biochar be used as a seed coating to improve native plant germination and growth in arid conditions? *Journal of Arid Environments*, 125, 8–15. <https://doi.org/10.1016/j.jaridenv.2015.09.011>
- Zvinavashe, A. T., Laurent, J., Mhada, M., Sun, H., Fouda, H. M. E., Kim, D., ... & Marelli, B. (2021). Programmable design of seed coating function induces water-stress tolerance in semi-arid regions. *Nature Food*, 2, 485–493. <https://doi.org/10.1038/s43016-021-00315-8>

Chapter 2 - Short-Term Storage Temperature Effects on Coated and Noncoated Turfgrass Seed

Abstract

Turfgrass practitioners and seed supplier stores often store seed for short intervals (one to six months) at different times of the year. Information is lacking on the effects of storage temperature on the germination and viability of coated and noncoated turfgrass seeds. This study quantified the effect of short-term (one-month) storage temperature stress on germination and seedling vigor of coated and noncoated cool-season turfgrass seeds. Two laboratory experiments evaluated two seed coatings (coated vs. noncoated) subjected to storage temperatures (4, 22, 42, 62, or 82 °C) across four turfgrass species: tall fescue (*Festuca arundinacea* Schreb.), Kentucky bluegrass (*Poa pratensis* L.), strong creeping red fescue (*Festuca rubra* L. ssp. *rubra* Gaudin), and perennial ryegrass (*Lolium perenne* L.). Germination, mean germination time, seedling vigor, and seed moisture were measured, and days to 50% germination were estimated using a four-parameter sigmoidal regression model. Seed moisture declined by 65–72% at 62 °C as compared with the average moisture content at 4 and 22 °C. Germination remained high at 4, 22, and 42 °C but declined at 62 °C and was <1% at 82 °C, indicating a critical heat stress threshold. Seed coating effects were species-dependent: tall fescue and strong creeping red fescue showed improvement in germination and emergence, whereas perennial ryegrass and Kentucky bluegrass exhibited reduced performance. Overall, short-term heat stress was the primary cause of deterioration, and the coating neither retained seed moisture nor prevented high-temperature damage. Maintaining cool storage conditions is essential for preserving turfgrass seed viability and vigor.

Introduction

Seed viability and vigor are critical traits for successful turfgrass establishment. Viability is defined as the ability to germinate into a normal seedling, whereas vigor is more complex and encompasses aging tolerance, seed dormancy, and viability, which is reflected in rapid and uniform emergence under suboptimal conditions (Reed et al., 2022). Both traits are strongly influenced by storage conditions, such as temperature, humidity, and duration (Silva et al., 2022). Seed deterioration is an irreversible process resulting from cellular and metabolic damage, including enzyme loss, membrane disruption, and nucleic acid degradation (El-Maarouf-Bouteau et al., 2011; Fleming et al., 2019; Goel et al., 2003; Harman & Mattick, 1976; Kranner, 2013). Although seed deterioration is often associated with long-term storage, it may also occur within a short timeframe under unfavorable storage conditions, such as extreme heat and excess humidity (De Vitis et al., 2020). Thus, understanding how short-term storage under suboptimal conditions, such as heat stress, impacts seed health is essential for maintaining seed viability and proper establishment of turfgrasses (see Chapter 1).

Cool, dry storage conditions reduce seed deterioration (Ackigoz & Knowles, 1983), as evidenced by 80–90% viability in crested wheatgrass (*Agropyron cristatum* L. Gaertn.), intermediate wheatgrass (*Agropyron intermedium* Host. Beauv.), and smooth brome grass (*Bromus inermis* Leyss.) after 20 years of storage at -7 to -18 °C. Bass and Stanwood (1978) also reported acceptable viability of sorghum seed (*Sorghum bicolor* L. Moench.) when stored at -1 and -12 °C for 16 years. Similarly, in grasses, Rincker and Maguire (1979) and Rincker (1981) found similar or better germination for orchardgrass (*Dactylis glomerata* L.), smooth brome grass, timothy (*Phleum pratense* L.), and poor germination in older seeds of meadow fescue (*Festuca elatior* L.) when stored for 14 years at -15 °C and 60% relative humidity

compared to fresh (i.e., new) seeds. These studies emphasize the critical role of storage temperature and humidity in maintaining seed health across various plant species. However, research with commonly used cool-season turfgrass species is lacking.

In turfgrasses, studies have shown that Kentucky bluegrass (*Poa pratensis* L.), red fescue (*Festuca rubra* L.), and Chewings fescue [*Festuca rubra* L. ssp. *commutata* Gaudin; syn. *F. rubra* ssp. *fallax* (Thuill.) Nyman], and orchardgrass maintained close to the original germination levels for at least 8 years when stored at -15°C under constant freezing or weekly freezing–thawing cycles (Rincker, 1986). Rincker, (1986) also reported that storage of these three grasses in unheated warehouses with fluctuations from -20 to 40°C caused a rapid decline in germination. Similarly, storing seeds at room temperature (23 to 30°C) resulted in severe germination losses in Kentucky bluegrass and red fescue within 5 years, whereas highland bentgrass (*Agrostis tenuis* Sibth.) maintained seed viability (Roberts, 1972). Similarly, zoysiagrass (*Zoysia japonica* Steud.) declined sharply under warm storage conditions (15 to 30°C), with germination falling from 96.5% to 40.5% over five years; however, cooler storage conditions (5 to 7°C) slowed the deterioration and preserved seed vigor (Mao et al., 2009; Qian et al., 2000). These studies highlight the species-specific nature of responses to seed storage conditions.

While extensive research has focused on long-term storage at low temperatures, the effects of short-term storage under heat stress remain less well understood, a situation that is particularly relevant given the unpredictable temperature fluctuations during summer storage. To address these challenges, innovative storage solutions, such as climate-controlled environments or specialized storage containers, have been implemented; however, their adoption is often constrained by the availability of appropriate facilities, funding, or awareness. Storing seeds in

suboptimal environments (e.g., a non-climate-controlled building or vehicle) requires further investigation. The turfgrass industry has explored the potential of seed-coating technology over the last thirty years to enhance seed germination and establishment (see Chapter 1 for a comprehensive review). Seed coating involves applying materials such as natural or synthetic polymers or hydrogels to the seed surface, which can improve seed spread or seed visualization at seeding, germination, and seedling development while providing protective benefits such as moisture retention and insulation against temperature fluctuations (Avelar et al., 2012; Leinauer et al., 2010; Pedrini et al., 2020; Scott, 1989; Serena et al., 2012a). However, the benefits of seed coatings remain inconsistent and species-dependent across various plant and turfgrass species. While these coating materials are designed to enhance seed performance (i.e., germination) during establishment, it is not well understood whether they offer similar protective effects during storage, particularly under high temperatures. Investigating the potential role of seed coatings in mitigating storage-related loss of viability could help refine seed storage recommendations. Therefore, the objectives of these experiments were to evaluate the effects of short-term (one-month) storage at multiple temperatures on the germination and viability of coated and noncoated cool-season turfgrass seeds.

Materials and Methods

Experimental design

Two controlled-environment laboratory experiments were conducted at Kansas State University, Manhattan, KS, between 2023 and 2025. Both experiments were repeated over time. The treatment structure was a two-way factorial arranged in a completely randomized design with four replications in both experiments. In both experiments, treatment factor 1 consisted of

noncoated and coated seed of cool-season turfgrass species: tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] (TF), Kentucky bluegrass (KB), strong creeping red fescue (*Festuca rubra* L. ssp. *rubra* Gaudin) (SCRF), and perennial ryegrass (*Lolium perenne* L.) (PR) (perennial ryegrass – included in Experiment 1 only). Information on species, cultivars or blends, coating composition, and seed companies is presented in Table 2.1. Treatment factor 2 consisted of varying storage temperatures (Experiment 1: 4, 22, 42, and 62 °C; Experiment 2: 22, 62, and 82 °C). In both experiments, 6 g of seed were placed in 12.7 × 8.3 cm paper envelopes and arranged in their respective storage environments. The one-month storage temperature environments corresponded to the following: i) refrigerator (4 °C); ii) climate-controlled room (22 °C); iii) or forced-air ovens [Fisher Scientific Isotemp 737F Oven (Thermo Fisher Scientific, Waltham, MA), VWR Signature Reach-in Incubator Model 1915a, (VWR International LLC., Radnor, PA)] (42, 62, or 82 °C). Temperature and relative humidity were monitored using data loggers (MX1101, Onset Computer Corp., Bourne, MA, USA) in the 4 and 22 °C storage conditions, and with thermocouples (UX100, Onset Computer Corp.) in the 42 to 82 °C storage conditions.

Table 2.1. Species, cultivars or blends, coating composition, and seed companies' information.

Species	Cultivar/Blend	Coating composition	Company
Experiment 1			
Tall fescue	Dynamite G-LS	Noncoated or coated with 1% limestone super-absorbent	Mountain View Seeds (Salem, OR, USA)
Kentucky bluegrass	Selway		
Strong creeping red fescue	Cardinal II		
Perennial ryegrass	Fastball 3GL		
Experiment 2			
Tall fescue	RTF (TF blend) 'Barmesh' 'Flame' 'Zion' 'Bonfire'	Noncoated or coated Coating name and information for both TF & KB: Yellow Jacket Includes: Limestone base (≈50% of coating weight; inert material + dried actives) Starch-based superabsorbent Apron XL fungicide Fertility treatment	Barenbrug USA (Tangent, OR, USA)
Kentucky bluegrass	HGT (KB blend) 'Barserati' 'Barvette' 'Barrister' 'Barimpala' 'Barrari' 'Barduke'		
Strong creeping red fescue	Cardinal II	Noncoated or coated with 1% limestone super-absorbent	Mountain View Seeds (Salem, OR, USA)

Note: Representative coated and noncoated seeds are shown in Appendix Figure A.1.

Data collection

Seed moisture content

Seed moisture content was determined using the air-oven method in accordance with the Association of Official Seed Analysts (AOSA) protocol (Association of Official Seed Analysts, 2016). From each seed envelope, 5 g of seed were weighed (fresh weight) and dried in a forced-air oven at 130 °C for 3 h. After drying, seeds were reweighed (dry weight), and moisture content was calculated as a percentage of the fresh weight using the Equation [Eq. 1], described by Hay et al. (2023) and Elias et al. (2012a):

$$\text{Seed Moisture Content (\% fresh weight)} = \frac{\text{Initial seed weight (fresh weight,g)} - \text{Final Weight (dry weight,g)}}{\text{Initial seed weight (fresh weight,g)}} \times 100 \quad [\text{Eq. 1}].$$

Germination speed and percentage

Seed germination percentage was evaluated following the AOSA protocols (Association of Official Seed Analysts, 2016). From each envelope, ~125 seeds per species were placed on blue blotter paper (PBB 325, Hoffman Manufacturing, Inc.) in 100 × 15 mm Petri dishes. Each treatment combination (seed coating × storage temperature) was replicated four times. Blotter papers were moistened as needed with 0.2% KNO₃ solution and incubated in a growth chamber (E15, CM324, Conviron Inc.) programmed for 25/15 °C (day/night) with an 8-h photoperiod during the day at 110 μmol m⁻² s⁻¹ photosynthetic photon flux. Seeds were monitored daily for 28 d, and germination was recorded for each seed when both radicle and coleoptile were visible. Germinated seeds were removed after counting, and Petri dishes were randomized daily on trays in the growth chamber. At the final count (day 28), non-germinated seeds were counted. The total germination percentage was calculated. Germination speed was estimated from cumulative germination percentage over time regressed against days following Braun et al. (2023). This analysis was performed using GraphPad Prism (v.10.3, GraphPad Software Inc., San Diego, CA) and a four-parameter sigmoidal regression model represented by Equation [Eq. 2]:

$$y = \text{Bottom} + \frac{\text{Top} - \text{Bottom}}{1 + \left(\frac{\text{DG}_{50}}{x}\right)^{\text{Hillslope}}} \quad [\text{Eq. 2}].$$

where y is the germination percentage, Bottom and Top represent the lower and upper values of germination percentage, respectively, DG₅₀ is the x value when the response of DG₅₀, which is halfway between Bottom and Top (days until 50% germination), and Hillslope (no units) describes the slope of the curve at DG₅₀. Values for DG₅₀ were obtained from the regression curves.

Mean germination time (MGT, d) was also calculated for each Petri dish following Ellis and Roberts (1980) and Larsen and Andreasen (2004) using Equation [Eq. 3]:

$$\text{MGT} = \frac{\sum n_i d_i}{\sum n_i} \quad [\text{Eq. 3}].$$

where n_i is the number of seeds that germinated in time i (not the accumulated number, but the number corresponding to the i^{th} observation), and d_i is the number of days from the beginning of the germination test (incubation period) to the i^{th} observation.

Seedling vigor

Seedling vigor was assessed using the paper towel method (Association of Official Seed Analysts, 1983; Elias et al., 2012b). Twenty seeds from each envelope were placed between moist paper towels (25 × 38 cm, PG1015, Hoffman Manufacturing Inc.) for each replication. Towels were rolled, labeled, placed upright in plastic bags, and arranged in a randomized complete block design with four replications (each plastic bucket served as a block). Towels were incubated in the same growth chamber and under the same conditions as in the germination test. After 21 d, paper towels were unrolled, and the shoot and root lengths (mm) of each seedling were measured using a digital caliper. Seedlings with abnormal growth were excluded from measurements. Fresh shoot mass from each towel was pooled and weighed, then dried at 60 °C in a forced-air oven for 72 h, after which it was weighed again. Average fresh and dry shoot mass (g) per seedling was calculated by dividing the total mass by the number of seedlings measured for each towel.

Data analysis

Data from both experiments were analyzed using analysis of variance (ANOVA) in SAS 9.4 (SAS Institute Inc., Cary, NC) with the GLIMMIX procedure to test main effects and interactions within each turfgrass species. Treatments were treated as fixed effects, and replication (block) as a random effect. Residual normality was checked using the Shapiro–Wilk test (Shapiro & Wilk, 1965). For each experiment, the effect of experiment run was tested to

determine if data could be combined across runs. Treatment $\times$ run interactions were not significant for any response variable in either experiment; therefore, data were combined across runs for final analysis. For Experiment 2, data were log-transformed prior to analysis to meet the assumptions of normality, and means were back-transformed for interpretation. The 82 °C treatment was excluded from ANOVA because the sigmoidal regression model produced unstable estimates at this temperature. Sigmoidal regression and correlation analyses were conducted using GraphPad Prism (GraphPad Software, San Diego, CA). Means were separated using Fisher's protected LSD test at $\alpha = 0.05$ when F -tests were significant ($P \leq 0.05$).

In addition to ANOVA, germination percentage was analyzed using quadratic regression to characterize the relationship between storage temperature and germination percentage across all cool-season turfgrass species combined across both experiments. Storage temperature was treated as a continuous variable, and seed coating treatment (coated vs. noncoated) was included as a fixed factor. The model included linear and quadratic temperature terms, as well as their interactions with the coating treatment. Regression analysis was conducted in R version 4.3.1 (R Foundation for Statistical Computing, Vienna, Austria), and the coefficient of determination (R^2) was used to evaluate model fit. Predicted optimum storage temperatures and their 95% confidence intervals were estimated from the fitted quadratic models using the delta method.

To evaluate the relationships among seed quality parameters across both short-term storage experiments, a Pearson correlation analysis (r) was conducted in R (version 4.4.2) using the *Hmisc* package. Parameters included seed moisture content, germination percentage, top germination percentage, mean germination time, days to 50% germination, average shoot dry weight, shoot length, and root length. Statistical significance was determined at $P < 0.05$, $P <$

0.01, and $P < 0.001$. Correlation analysis was used as a complementary approach to summarize overall relationships among seed quality traits and to support interpretation of treatment effects.

Results and Discussion

Seed moisture content

A significant seed coating $\times$ storage temperature interaction was observed for seed moisture content within each turfgrass species in both experiments (Figures. 2.1 and 2.2; $P < 0.0001$).

In Experiment 1, seed moisture content remained high at 4 and 22 °C for noncoated seed across all species and declined progressively with increasing storage temperature (Figure. 2.1). Coated seed consistently had lower absolute moisture than noncoated seed at each respective storage temperature. Additionally, the coating did not help regulate seed moisture content under heat stress. At 42 °C, seed moisture content decreased by 45 to 47% for noncoated seed and similarly, it decreased by 43 to 46% for coated seed compared with the average moisture content at 4 and 22 °C across all species. Storage at 62 °C resulted in even greater drying of seed moisture content, with moisture content reduced by 69 to 72% for noncoated seed and 65 to 69% for coated seed compared with the average moisture content at 4 and 22 °C. The proportional reduction was similar for both coating treatments, indicating that high storage temperatures (42 and 62 °C) resulted in comparable moisture loss regardless of coating. This suggests that the coating did not mitigate the severe drying imposed by the highest temperature. The consistent responses across all species indicate that storage temperature was the dominant factor regulating seed moisture content, whereas coating primarily shifted overall moisture levels without altering the temperature response.

In Experiment 2, seed moisture content declined sharply as storage temperature increased from 22 to 82 °C (Figure. 2.2). At 62 °C, moisture content decreased by 73 to 77% for noncoated seed and 73 to 79% for coated seed compared with 22 °C storage temperature, which falls within a range similar to that observed in Experiment 1. Exposure to 82 °C resulted in 73 to 100% moisture loss across species, regardless of coating, indicating severe desiccation and likely seed death (e.g., minimal-to-no germination occurred).

Across both experiments, coated seed consistently started with and maintained lower moisture levels than noncoated seed after only one month of storage. This difference reflected lower initial moisture, as the seed coating process, which includes slurry application followed by drum or forced-air drying, removes moisture during production, resulting in a lower seed moisture content at the start. Consequently, coated seeds had less moisture available to lose; regardless, the percent reductions in seed moisture observed across temperatures were within a similar range for both noncoated and coated seed.

Although reduced seed moisture content can slow seed deterioration under mild conditions (Bakhtavar & Afzal, 2021), the extreme drying observed at higher temperatures is more likely to impair metabolic function and damage cellular reserves required for germination and vigor (Adams & Rinne, 1980; Kranner, 2013). Consistent with general seed-storage principles (Ellis & Roberts, 1980), short-term exposure to elevated temperatures greatly accelerated moisture loss from seed tissues, and the seed coatings used in this study did not protect seeds from drying. Storage temperatures above 22 °C resulted in progressively greater reductions in seed moisture content; therefore, managers need to be mindful of storage temperatures regardless of whether the seed is coated. For the seed industry and turfgrass managers, maintaining cool, stable storage temperatures remains the most effective strategy to

preserve seed moisture content, and seed coating is not helpful in preventing loss of seed moisture content.

Germination parameters

Germination percentage

Seed coating effects on germination percentage were species-specific in Experiment 1 (Table 2.2). Germination increased by approximately 1 to 16% with seed coating in TF and SCRF relative to noncoated seed. In contrast, coated PR exhibited a 7% decrease in germination, whereas coating did not affect KB. Despite these species-level differences, germination remained high across all treatments, and the magnitude of coating effects was small, indicating limited practical benefit of coating under the short-term storage conditions evaluated. These mixed responses suggest species-specific effect of coating, consistent with previous studies (Greipsson, 1999; Layton et al., 2007; Munshaw et al., 2014; Newell, 1997; Richardson & Hignight, 2010; Serena et al., 2012b).

Storage temperature also influenced germination in Experiment 1, with only slight reductions (0 to 3% reductions at 42 °C and 3 to 7% reductions at 62 °C) compared with the average germination at 4 and 22 °C across species, except for KB. No significant coating × temperature interactions were observed, indicating that the coating did not alter the temperature response of germination. These results align with previous studies showing that short-term exposure to elevated temperatures can initiate seed deterioration in cool-season grasses (Ackigoz & Knowles, 1983; Nutile, 1964; Qian et al., 2000; Rincker, 1986; Roberts, 1972).

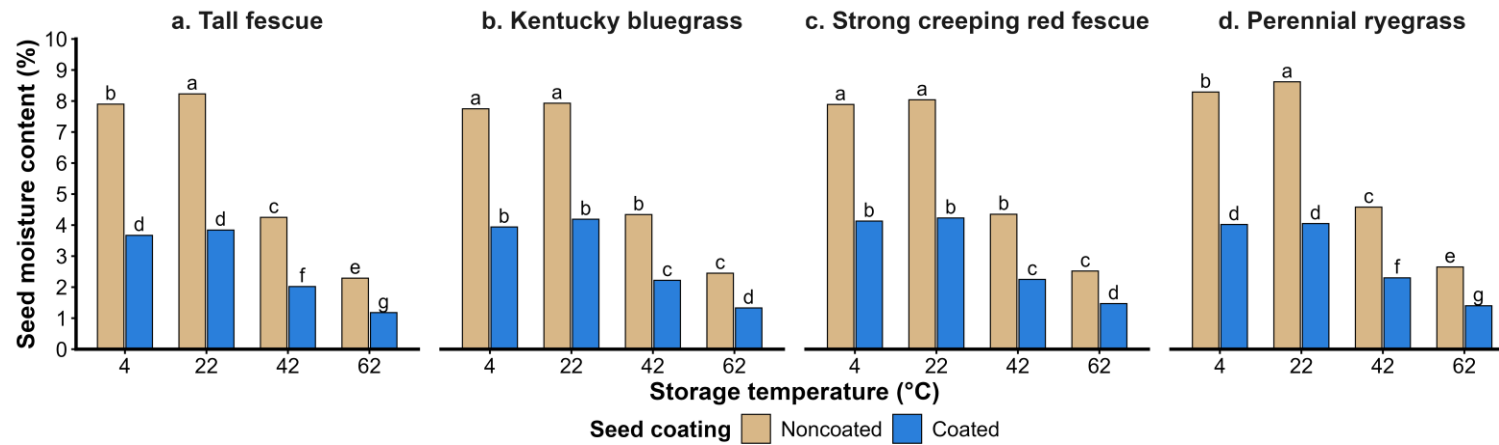


Figure 2.1. Interaction effect of seed coating and storage temperature on seed moisture content within each of the four cool-season turfgrass species in Experiment 1: (a) tall fescue, (b) Kentucky bluegrass, (c) strong creeping red fescue, and (d) perennial ryegrass. *Note:* Means within each species followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Statistical comparisons are not across species.

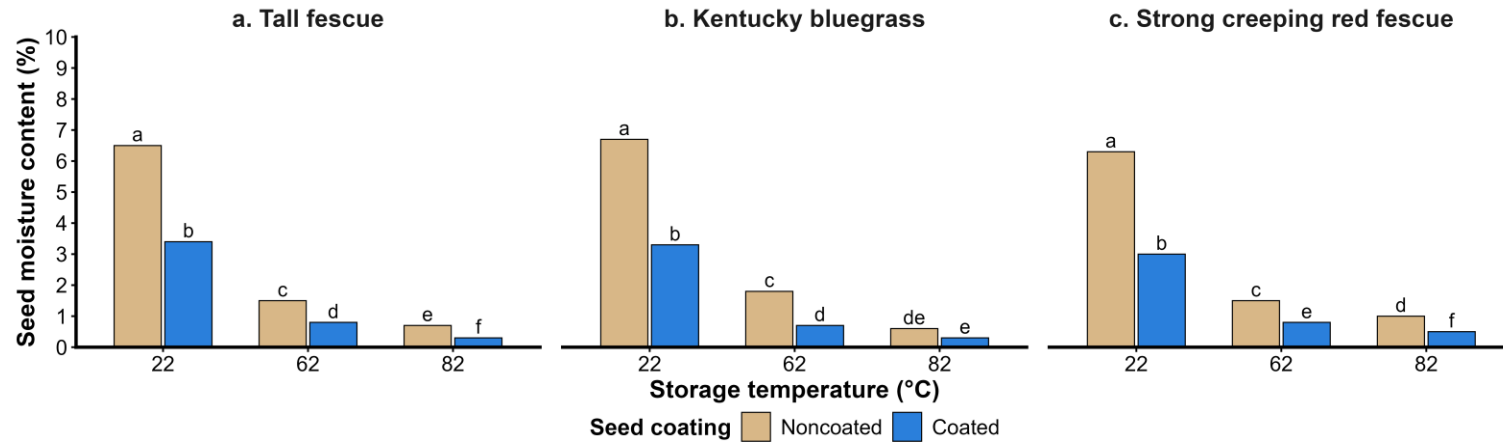


Figure 2.2. Interaction effect of seed coating and storage temperature on seed moisture content within each of the three cool-season turfgrass species in Experiment 2: (a) tall fescue, (b) Kentucky bluegrass, and (c) strong creeping red fescue. *Note:* Means within each species followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Statistical comparisons are not across species.

In Experiment 2, coating reduced germination in TF and KB only, with the largest reduction occurring in KB (59% reduction), followed by TF (10% reduction), and no differences in noncoated vs coated seed in SCRF (Table 2.3). Storage temperatures were the dominant factor affecting germination. KB exhibited a 23% decline at 62 °C compared with 22 °C, while germination decreased by 98 to 99% at 82 °C across all species, indicating a critical temperature threshold beyond which seed viability could not be maintained. A significant seed coating × storage temperature interaction occurred only in KB ($P < 0.0001$). At 22 °C, coated KB showed a 41% reduction in germination percentage compared with noncoated seed, indicating a substantial decline even under favorable storage conditions (data not shown). At 82 °C, germination in KB was near zero (0.5%) for both noncoated and coated seed, demonstrating that extreme heat stress eliminated any coating-related differences. These results for KB at 22 and 62 °C were surprising, as we did not observe these trends in Experiment 1.

To further characterize the temperature response, germination percentage was modeled using quadratic regression, with coated and noncoated seeds showing similar temperature response patterns (Figure. 2.3). When data from all cool-season turfgrass species and both experiments were combined, germination exhibited a quadratic response to storage temperature. The fitted quadratic models predicted maximum germination at 30.1 °C (95% CI: 27.8–32.4 °C) for noncoated seed and 27.6 °C (95% CI: 24.8–30.5 °C) for coated seed. Although the coated seed regression curve appeared to decline slightly faster at higher temperatures, the overlapping confidence intervals indicate similar temperature optima between seed coating treatments. Germination declined slightly at 42 °C and more sharply at 62 and 82 °C. The quadratic regression model provided a good overall fit to the data ($R^2 = 0.673$), indicating that storage

temperature had a stronger influence on germination than seed coating treatment, consistent with the ANOVA results.

Across both experiments, storage temperature exerted a more consistent influence on germination than seed coating, while coating effects were species-dependent with minimal benefits. Germination remained relatively stable at lower storage temperatures but declined sharply under elevated and extreme heat conditions, reinforcing the importance of maintaining cool, stable storage conditions to preserve turfgrass seed viability, consistent with the storage and germination patterns (see Chapter 1). The seed coatings evaluated in this study did not enhance heat-stress tolerance, and therefore, appropriate temperature management during storage is critical.

Table 2.2. Effect of seed coating and storage temperature on germination percentage of four cool-season turfgrass species in Experiment 1.

Species	Tall fescue	Kentucky bluegrass	Strong creeping red fescue	Perennial ryegrass
Germination (%)				
Seed coating				
Noncoated	90.6 b	89.2	70.7 b	92.0 a
Coated	92.0 a	89.9	81.7 a	85.7 b
Storage temperature				
4 °C	92.4 a	89.6	78.3 a	90.5 a
22 °C	92.4 a	89.6	77.6 a	90.3 a
42 °C	91.6 a	89.4	76.4 a	88.1 ba
62 °C	88.8 b	89.6	72.5 b	86.3 b
<i>p</i> values				
Seed coating	0.0382	0.2662	<.0001	<.0001
Storage temperature	0.0002	0.9904	0.0194	0.0076
Seed coating × Storage temperature	0.1662	0.5615	0.8370	0.6354

Note: Means within a column of each main effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$).

Table 2.3. Effect of seed coating and storage temperature on germination percentage of three cool-season turfgrass species in Experiment 2.

Species	Tall fescue	Kentucky bluegrass	Strong creeping red fescue
Germination (%)			
Seed coating			
Noncoated	60.7 a	58.8 a	43.3
Coated	54.9 b	24.2 b	41.6
Storage temperature			
22 °C	90.3 a	70.5 a	64.5 a
62 °C	82.4 a	53.6 b	61.8 a
82 °C	0.8 b	0.5 c	1.0 b
<i>p</i> values			
Seed coating	0.0162	<.0001	0.2307
Storage temperature	<.0001	<.0001	<.0001
Seed coating × Storage temperature	0.1232	<.0001	0.4596

Note: Means within a column of each main effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$)

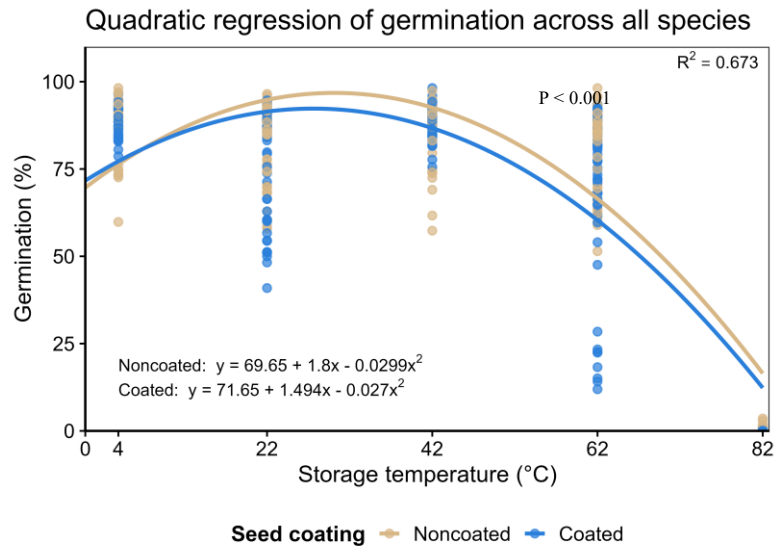


Figure 2.3. Quadratic regression of germination percentage in response to storage temperature for coated and noncoated seeds combined across all cool-season turfgrass species and both experiments ($n = 400$). *Note:* Points represent observed germination values at each storage temperature, and lines represent fitted quadratic regression models for each seed coating treatment. The coefficient of determination (R^2) and adjusted R^2 describe the goodness of fit of the regression model ($P < 0.001$).

Germination speed

Germination speed was assessed using DG₅₀ (days to 50% germination) and MGT (mean germination time). In Experiment 1, seed coating × storage temperature interactions were observed only in two species (KB and PR) (Table 2.4). In KB, both DG₅₀ and MGT increased (i.e., germination was slower) with increasing storage temperature (42 and 62 °C), regardless of coating, indicating progressively slower germination after being subjected to heat stress during storage. In PR, coating consistently increased DG₅₀ and MGT (i.e., slower germination speeds) across temperatures, with the greatest delay at 62 °C. This response suggests that the coating acted as a temporary physical barrier in this inherently fast-germinating species, slightly delaying radicle emergence.

Across species, coating and storage temperature effects on germination speed varied (Appendix Table A.1). Coated TF, KB, and SCRF germinated faster (lower DG₅₀ and MGT values) than noncoated seed, whereas coating delayed germination speed in PR. These species-dependent responses are consistent with previous reports indicating that certain seed coatings can delay early germination by acting as a temporary physical barrier, particularly in rapidly germinating turfgrass species (Richardson & Hignight, 2010; Serena et al., 2012b). Storage temperature had no influence on TF but increased DG₅₀ and MGT (i.e., slower germination speeds) at 62 °C in KB, SCRF, and PR, indicating slower germination of seed is expected following short-term heat stress during storage.

In Experiment 2, significant interactions were observed in TF and KB (Table 2.5). In TF, no differences were observed in DG₅₀ between coated and noncoated seed when stored at 22 °C, but differences in MGT were detected. Seed coating accelerated germination at 22 °C but slowed germination at 62 °C, indicating that seed coating benefits under room-temperature storage did

not persist under heat stress and that coating did not consistently maintain faster germination speeds. In KB, coated seed consistently exhibited higher DG₅₀ (germination was slower), with the greatest delay at 62 °C. These results align with Experiment 1. At 82 °C, germination was near zero (0.5–1%) across species; this treatment was excluded from the statistical analysis of mean comparisons due to unstable values since most of this treatment result in <1% germination percentage. This suggests that elevated storage temperatures strongly disrupt seed metabolic processes required for seed viability, consistent with previous findings in pea (*Pisum sativum* L.), another C₃ plant (Cojocaru et al., 2024).

Overall, germination speed was influenced by both seed coating and storage temperature in a species-dependent manner, with temperature exerting the stronger effect. For practical applications, avoiding elevated storage temperatures, even for short durations, is essential to maintain rapid and uniform emergence and coating turfgrass seed is not a solution to this problem.

Table 2.4. Interaction effect of seed coating and storage temperature on germination speed (DG₅₀ and MGT) in Kentucky bluegrass and perennial ryegrass in Experiment 1.

Species	Kentucky bluegrass		Perennial ryegrass	
	DG ₅₀	MGT	DG ₅₀	MGT
days				
Seed coating × Storage temperature				
Noncoated × 4 °C	9.9 dc	10.8 d	5.5 c	6.4 ced
Noncoated × 22 °C	9.8 dce	10.7 d	4.8 d	5.7 f
Noncoated × 42 °C	11.4 a	12.1 b	5.1 dc	6.0 fe
Noncoated × 62 °C	11.6 a	12.6 a	5.4 c	6.4 ed
Coated × 4 °C	9.5 de	10.4 f	5.9 b	6.9 cb
Coated × 22 °C	9.4 e	10.2 f	6.0 b	6.9 b
Coated × 42 °C	10.1 c	11.0 d	6.0 b	6.8 cbd
Coated × 62 °C	10.8 b	11.5 c	7.0 a	7.8 a
<i>p</i> values				
Seed coating × Storage temperature	0.0269	0.0057	0.0132	0.0329

Note: Means within a column followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). DG₅₀ (days) represents the estimated time to 50% germination derived from a four-parameter sigmoidal regression model, and MGT (days) represents mean germination time.

Table 2.5. Interaction effect of seed coating and storage temperature on germination speed (DG₅₀ and MGT) in tall fescue and Kentucky bluegrass in Experiment 2.

Species	Tall fescue		Kentucky bluegrass	
	DG ₅₀	MGT	DG ₅₀	MGT
days				
Seed coating × Storage temperature				
Noncoated × 22 °C	9.1 ab	10.2 ab	6.5 d	7.3
Noncoated × 62 °C	8.6 b	9.6 bc	7.6 c	8.7
Coated × 22 °C	8.0 b	8.9 c	10.6 b	11.7
Coated × 62 °C	10.1 a	11.0 a	13.9 a	14.5
<i>p</i> value				
Seed coating × Storage temperature	0.0034	0.0028	0.0459	0.3577

Note: Means within a column followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). DG₅₀ (days) represents the estimated time to 50% germination derived from a four-parameter sigmoidal regression model, and MGT (days) represents mean germination time. Data at 82 °C were excluded from model fitting due to near-zero germination, resulting in unstable regression estimates. Values shown are back-transformed means, whereas statistical analyses were performed on log ($y + 0.5$)-transformed data.

Seedling vigor

Seedling vigor was assessed by measuring shoot and root length at 21 days, with average shoot dry weight measured as supporting data. However, average shoot dry weight was not influenced by seed coating or storage temperature in either experiment; therefore, data are not shown.

In Experiment 1, seed coating effects on shoot and root length were small and species-dependent (Figure. 2.4). Coating slightly increased shoot (6%) and root (8%) length in SCRF but reduced shoot (5%) and root (8%) length in PR. In TF, coating increased root length by 8% but did not affect shoot length, whereas no coating effects were observed in KB. Storage temperature had no effect on seedling growth in most species; however, in SCRF, root length at 62 °C was reduced by 15% compared with the average root length at 4, 22, and 42 °C. No coating $\times$ temperature interactions were observed for any species. Overall, these results indicate that both coating and storage temperatures had limited and species-specific effects on early seedling growth.

In Experiment 2, storage temperature was the dominant factor affecting seedling growth (Figure. 2.5), likely due to the higher storage temperature treatments imposed. Across all three species, shoot and root lengths were greatest when the seeds were stored at the more ideal temperature of 22 °C. Storage at 82 °C caused severe reductions in shoot and root length (86–98%) compared with mean seedling growth at 22 and 62 °C. A coating $\times$ temperature interaction was detected only in KB, where coated seed stored at 62 °C exhibited shoot and root lengths 75 to 78% lower than those of noncoated seed at the same temperature. However, at the extreme storage temperature of 82 °C, shoot and root growth were reduced by approximately 98% across all coating treatments.

Overall, both experiments demonstrated that storage temperature exerted a greater influence on seedling vigor than coating treatment, with extreme heat stress consistently reducing shoot and root growth across species. Seed coating did not mitigate heat-induced stress reductions in shoot or root length and provided no consistent advantage in seedling vigor. These patterns align with responses in germination percentage and speed, further demonstrating that the coating materials evaluated in this study do not confer greater heat stress tolerance and provide limited benefits during early establishment, when seeds are exposed to stressful storage conditions.

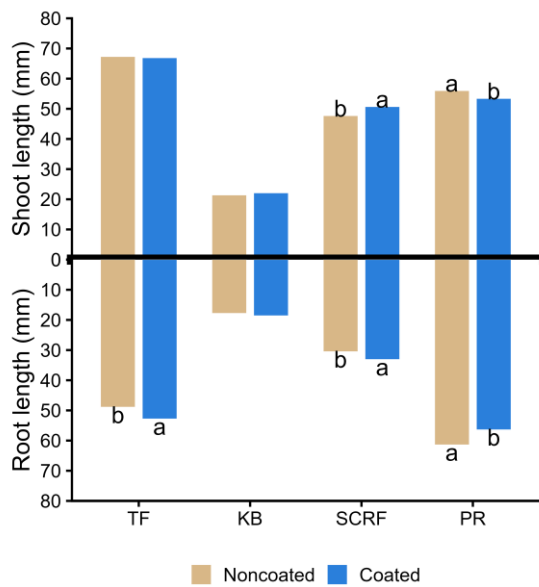


Figure 2.4. Effects of seed coating on shoot and root length of tall fescue (TF), Kentucky bluegrass (KB), strong creeping red fescue (SCRF), and perennial ryegrass (PR) in Experiment 1. *Note:* Different letters on bars indicate significant differences among means within each species at $\alpha = 0.05$ according to Fisher's protected LSD test.

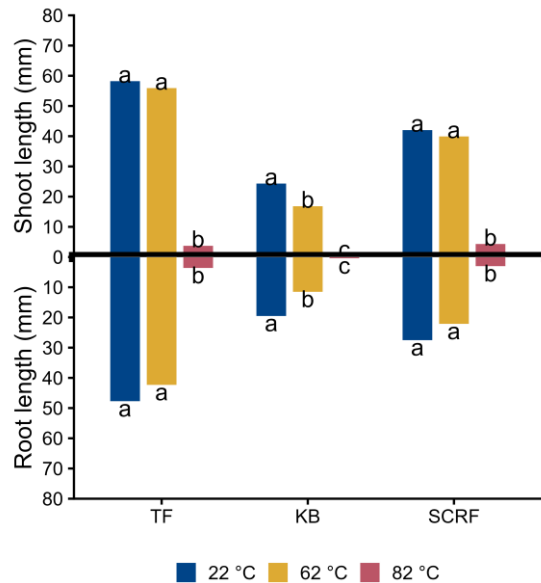


Figure 2.5. Effects of storage temperature on shoot and root length of tall fescue (TF), Kentucky bluegrass (KB), and strong creeping red fescue (SCRF) in Experiment 2. *Note:* Different letters on bars indicate significant differences among means within each species at $\alpha = 0.05$ according to Fisher's protected LSD test. Mean values represent back-transformed means; statistical analyses were performed on $\log(y + 0.5)$ -transformed data.

Pearson correlation analysis

Pearson correlation analysis showed strong relationships among seed moisture content, germination, germination speed, and seedling vigor traits across both short-term storage experiments (Figure 2.6). Germination percentage was strongly and positively correlated with top germination percentage ($r = 1.00$), shoot length ($r = 0.69$), root length ($r = 0.68$), and average shoot dry weight ($r = 0.52$), indicating that seed lots with higher germination also produced larger and more vigorous seedlings. In contrast, germination percentage was negatively correlated with MGT ($r = -0.41$) and DG_{50} ($r = -0.41$), demonstrating that greater germination was associated with faster germination. Similarly, MGT and DG_{50} were almost perfectly correlated ($r = 0.99$), confirming that both variables consistently described germination speed. Shoot and root length were also strongly correlated ($r = 0.90$), and both were positively

associated with average shoot dry weight, suggesting that early seedling growth traits responded together. Seed moisture content showed moderate positive correlations with germination and seedling growth traits but weak negative correlations with germination timing traits. Overall, these relationships indicate that elevated short-term storage temperatures reduced seed quality through multiple interrelated responses, including lower germination, slower germination, and reduced seedling growth, while the limestone-based seed coating did not consistently improve performance under heat stress.

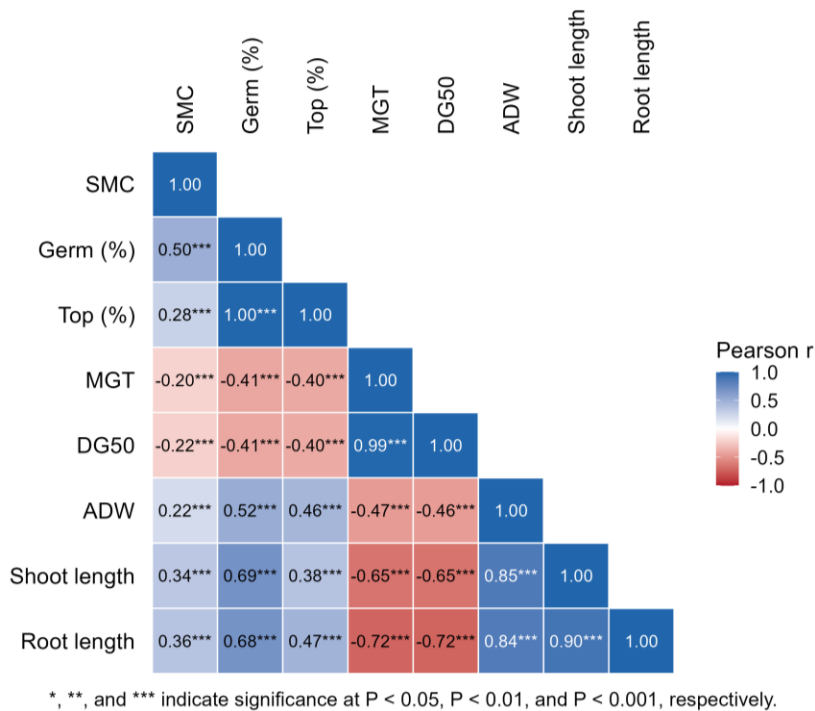


Figure 2.6. Pearson correlation matrix showing relationships among seed moisture content, germination, emergence, and seedling growth traits across Experiments 1 and 2. *Note:* SMC, seed moisture content (%); Germ, germination (%); Top, top germination percentage (%); MGT, mean germination time (d); DG₅₀, days to 50% germination (d); ADW, average seedling dry weight (mg); Shoot length (cm); Root length (cm). Values shown are Pearson correlation coefficients (r). Blue and red colors indicate positive and negative correlations, respectively, with darker colors representing stronger relationships. Only the lower triangle of the correlation matrix is displayed. *, **, and *** indicate statistical significance at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

Conclusions

Short-term storage temperature was the dominant factor affecting cool-season turfgrass seed viability and seed performance. Across both experiments, exposure to elevated storage temperatures (≥ 42 °C), even for a short duration of one month, accelerated seed moisture loss and progressively reduced germination percentage, germination speed, and seedling vigor, with near-complete loss of seed viability at 82 °C.

The seed moisture content of both noncoated and coated seeds declined rapidly as storage temperature exceeded 42 °C. For coated seed, the seed moisture content was lower at initiation, likely due to the seed-coating process. Therefore, greater caution is warranted regarding coated seed and seed moisture content, because the limestone-based coating may increase the risk of desiccation under heat stress rather than protecting seeds from drying, highlighting the potential downside of this formulation.

Seed-coating effects were species-specific: TF and SCRF showed slightly faster germination and, in some cases, greater early growth with coating, whereas PR performance declined and KB exhibited minimal response. These effects were strongly influenced by storage temperature; benefits observed at refrigerated (4 °C) or room (22 °C) temperatures did not persist under heat stress, and coating did not mitigate temperature-induced declines in seed performance.

Overall, these findings demonstrate that although some reports indicate that seed-coating technologies influence turfgrass germination and establishment, they cannot substitute for proper storage practices. For turfgrass managers, growers, and the seed industry, particularly in short-term storage, maintaining cool temperatures and stable conditions remains the most reliable strategy for preserving seed quality. Coating turfgrass seed offers only limited, species-

dependent benefits. For context, the optimal storage conditions that do not influence turfgrass seed health include refrigeration ($\sim 4^{\circ}\text{C}$) or indoor “room” temperature controlled by an HVAC system ($\sim 22^{\circ}\text{C}$). Whereas storage of turfgrass seed in a non-climate-controlled building, vehicle, or similar environment (~ 42 to 82°C) can significantly reduce seed health and lead to seed death. Future research should focus on refining coating formulations, such as advanced hydrogels or bio-based materials, that reduce desiccation and enhance resilience to variable storage environments, thereby broadening the practical value of seed coatings in turfgrass systems.

References

- Ackigoz, E., & Knowles, R. P. (1983). Long-term storage of grass seeds. *Canadian Journal of Plant Science*, 63, 669–674. <https://doi.org/10.4141/cjps83-084>
- Adams, C. A., & Rinne, R. W. (1980). Moisture content as a controlling factor in seed development and germination. In *International Review of Cytology* (Vol. 68, pp. 1–8). Academic Press. [https://doi.org/10.1016/S0074-7696\(08\)62305-0](https://doi.org/10.1016/S0074-7696(08)62305-0)
- Association of Official Seed Analysts. (1983) Seed Vigor Testing Handbook Contribution No. 32 to The Handbook on Seed Testing. East Lansing, MI. pp.22, 71–74.
- Association of Official Seed Analysts. Volume, 1. (2016). Principles and procedures, 2016. Association of Official Seed Analysts, Inc.
- Avelar, S. A. G., Sousa, F. V. D., Fiss, G., Baudet, L., & Peske, S. T. (2012). The use of film coating on the performance of treated corn seed. *Revista Brasileira de Sementes*, 34, 186–192. <https://doi.org/10.1590/S0101-31222012000200001>
- Bakhtavar, M. A., & Afzal, I. (2021). *Seed Storage and Longevity: Mechanism, Types and Management*. In A.K. Tiwari (ed.), *Advances in seed production and management* (pp. 451–468). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-15-4198-8_21
- Bass, L. N., & Stanwood, P. C. (1978). Long-term preservation of sorghum seed as affected by seed moisture, temperature, and atmospheric environment. *Crop Science*, 18, 575–577. <https://doi.org/10.2135/cropsci1978.0011183X001800040012x>
- Braun, R. C., Courtney, L. E., & Patton, A. J. (2023). Seed morphology, germination, and seedling vigor characteristics of fine fescue taxa and other cool-season turfgrass species. *Crop Science*, 63, 1613–1627. <https://doi.org/10.1002/csc2.20936>
- Cojocar, A., Carbune, R. V., Teliban, G. C., Stan, T., Mihalache, G., Rosca, M., ... & Stoleru, V. (2024). Physiological, morphological and chemical changes in pea seeds under different storage conditions. *Scientific Reports*, 14, 28191. <https://doi.org/10.1038/s41598-024-79115-6>
- De Vitis, M., Hay, F. R., Dickie, J. B., Trivedi, C., Choi, J., & Fiegner, R. (2020). Seed storage: maintaining seed viability and vigor for restoration use. *Restoration Ecology*, 28, S249–S255. <https://doi.org/10.1111/rec.13174>
- Elias, S. G., Copeland, L. O., McDonald, M. B., & Baalbaki, R. Z. (2012b). Speed of germination and seedling growth rate. *Seed Testing: Principles and Practices*. Michigan State University Press, East Lansing. pp. 155–192.
- Elias, S. G., Copeland, L. O., McDonald, M. B., & Baalbaki, R. Z. (2012a). Seed Moisture Content Testing. *Seed testing: Principles and practices*. Michigan State University Press, East Lansing, MI. pp. 257–270.

- Ellis, R. H., & Roberts, E. H. (1980). Towards a rational basis for testing seed quality. In P.D. Hebblethwaite (editor). *Seed Production*. Butterworths, London. p. 605–635.
- El-Maarouf-Bouteau, H., Mazuy, C., Corbineau, F., & Bailly, C. (2011). DNA alteration and programmed cell death during ageing of sunflower seed. *Journal of Experimental Botany*, 62, 5003–5011. <https://doi.org/10.1093/jxb/err198>
- Fleming, M. B., Hill, L. M., & Walters, C. (2019). The kinetics of ageing in dry-stored seeds: a comparison of viability loss and RNA degradation in unique legacy seed collections. *Annals of Botany*, 123, 1133–1146. <https://doi.org/10.1093/aob/mcy217>
- Goel, A., Goel, A. K., & Sheoran, I. S. (2003). Changes in oxidative stress enzymes during artificial ageing in cotton (*Gossypium hirsutum* L.) seeds. *Journal of Plant Physiology*, 160, 1093–1100. <https://doi.org/10.1078/0176-1617-00881>
- Greipsson, S. (1999). Seed coating improves the establishment of surface seeded *Poa pratensis* used in revegetation. *Seed Science and Technology*, 27, 1029–1032.
- Harman, G. E., & Mattick, L. R. (1976). Association of lipid oxidation with seed ageing and death. *Nature*, 260, 323–324. <https://doi.org/10.1038/260323a0>
- Hay, F. R., Rezaei, S., Wolkis, D., & McGill, C. (2023). Determination and control of seed moisture. *Seed Science and Technology*, 51, 267–285. <https://doi.org/10.15258/sst.2023.51.2.11>
- Kranner, I. (2013). Mechanisms of seed ageing. *South African Journal of Botany*, 86, 140–140. <https://doi.org/10.1016/j.sajb.2013.02.010>
- Larsen, S. U., & Andreassen, C. (2004). Light and heavy turfgrass seeds differ in germination percentage and mean germination thermal time. *Crop Science*, 44, 1710–1720. <https://doi.org/10.2135/cropsci2004.1710>
- Layton, J., Munshaw, G., Stewart, B., Baldwin, B., & Philley, H. (2007). Does seed coating affect bermudagrass germination? *ASA-CSSA-SSSA Annual Meeting Abstracts*. ASA, CSSA, and SSSA, Madison, WI.
- Leinauer, B., Serena, M., & Singh, D. (2010). Seed coating and seeding rate effects on turfgrass germination and establishment. *HortTechnology*, 20, 179–185. <https://doi.org/10.21273/HORTTECH.20.1.179>
- Mao, P. S., Wang, X. G., Wang, Y. H., & Han, J. G. (2009). Effect of storage temperature and duration on the vigor of zoysiagrass (*Zoysia japonica* Steud.) seed harvested at different maturity stages. *Grassland Science*, 55, 1–5. <https://doi.org/10.1111/j.1744-697X.2009.00129.x>
- Munshaw, G. C., Layton, J. M., Stewart, B. R., Philley, H. W., Beasley, J. S., & Lemus, R. W. (2014). The germination responses of five bermudagrass cultivars to seed coating and temperature. *HortScience*, 49, 1225–1229. <https://doi.org/10.21273/HORTSCI.49.9.1225>

- Newell, A. J. (1997). Effect of different seed treatments and coatings on the germination and establishment of four grass species. *Journal of Turfgrass Science*, 73, 67–72.
- Nutile, G. E. (1964). Effect of desiccation on viability of seeds. *Crop Science*, 4, 325–328. <https://doi.org/10.2135/cropsci1964.0011183X000400030028x>
- Pedrini, S., Balestrazzi, A., Madsen, M. D., Bhalsing, K., Hardegree, S. P., Dixon, K. W., & Kildisheva, O. A. (2020). Seed enhancement: getting seeds restoration-ready. *Restoration Ecology*, 28, S266–S275. <https://doi.org/10.1111/rec.13184>
- Qian, J.Z., Han, J.G., Ni, X.Q., Song, J.F. (2000). A study on physiological and biochemical changes in storing zoysia seed. *Acta Agrestia Sinica*, 3, 177–185.
- Reed, R. C., Bradford, K. J., & Khanday, I. (2022). Seed germination and vigor: ensuring crop sustainability in a changing climate. *Heredity*, 128, 450–459. <https://doi.org/10.1038/s41437-022-00497-2>
- Richardson, M. D., & Hignight, K. W. (2010). Seedling emergence of tall fescue and Kentucky bluegrass, as affected by two seed coating techniques. *HortTechnology*, 20, 415–417. <https://doi.org/10.21273/HORTTECH.20.2.415>
- Rincker, C. M. (1981). Long-term subfreezing storage of forage crop seeds. *Crop Science*, 21, 424–427. <https://doi.org/10.2135/cropsci1981.0011183X002100030017x>
- Rincker, C. M. (1986). Germination of grass seeds after 8 years of weekly removal from subfreezing storage. *Crop Science*, 26, 165–166. <https://doi.org/10.2135/cropsci1986.0011183X002600010039x>
- Rincker, C. M., & Maguire, J. D. (1979). Effect of seed storage on germination and forage production of seven grass cultivars. *Crop Science*, 19, 857–860. <https://doi.org/10.2135/cropsci1979.0011183X001900060027xa>
- Roberts, E. H. (1972). *Storage Environment and the Control of Viability. In Viability of seeds*, Dordrecht: Springer Netherlands. 14–58. https://doi.org/10.1007/978-94-009-5685-8_2
- Scott, J. M. (1989). Seed coatings and treatments and their effects on plant establishment. *Advances in Agronomy*, 42, 43–83. [https://doi.org/10.1016/S0065-2113\(08\)60523-4](https://doi.org/10.1016/S0065-2113(08)60523-4)
- Serena, M., Leinauer, B., Sallenave, R., Schiavon, M., & Maier, B. (2012b). Turfgrass establishment from polymer-coated seed under saline irrigation. *HortScience*, 47, 1789–1794. <https://doi.org/10.21273/HORTSCI.47.12.1789>
- Serena, M., Leinauer, B., Sallenave, R., Schiavon, M., & Maier, B. (2012a). Media selection and seed coating influence germination of turfgrasses under salinity. *HortScience*, 47, 116–120. <https://doi.org/10.21273/HORTSCI.47.1.116>

- Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, 52, 591–611. <https://doi.org/10.1093/biomet/52.3-4.591>
- Silva, J. C. D., Silva, J. D. J., Silva, S. S. D., Gomes, R. A., & Dantas, B. F. (2022). Effect of long-term storage on viability of buffel grass (*Cenchrus ciliaris* L.) seeds. *Journal of Seed Science*, 44, e202244008. <https://doi.org/10.1590/2317-1545v44259954>

Chapter 3 - The Influence of Long-term Storage Conditions on Coated and Noncoated Cool-Season Turfgrass Seed Germination and Seedling Vigor

Abstract

Proper seed storage is critical for maintaining turfgrass seed germination and vigor, yet little research has examined the effects of long-term (> 1 yr) storage conditions on coated and noncoated cool-season turfgrass seed. This study investigated the influence of long-term storage conditions on coated and noncoated seed of perennial ryegrass (*Lolium perenne* L.), tall fescue (*Festuca arundinacea* Schreb.), strong creeping red fescue (*Festuca rubra* L. ssp. *rubra* Gaudin), and Kentucky bluegrass (*Poa pratensis* L.). Seed was stored under three conditions: refrigerator (~4 °C), indoor (~22 °C), and non-insulated shed (~-25 to ~53 °C) for up to two years in a factorial experiment replicated across two locations in Manhattan, KS. Germination, mean germination time, seedling vigor, and seed moisture were measured, and days to 50% germination were estimated using a four-parameter sigmoidal regression model. Coated seed consistently exhibited lower seed moisture content (45–72% reduction) compared with noncoated seed across all storage conditions and durations. From Year 1 to Year 2, storage in the non-insulated shed resulted in the greatest germination losses, with declines of up to 80% in tall fescue and 55% in Kentucky bluegrass. In contrast, germination under indoor and refrigerated conditions remained relatively stable across both runs, with reductions $\leq 12\%$ from Year 1 to Year 2. These findings suggest that refrigerated or stable indoor storage is essential for preserving cool-season turfgrass seed germination and vigor, and seed coating may partially offset deterioration when storage is suboptimal.

Introduction

Turfgrasses have become an integral component of society because of their multiple uses, including home lawns, sports fields, golf courses, roadsides, sod farms, commercial properties, schools, parks, cemeteries, and other green spaces (Braun et al., 2024; Stier et al., 2013). Successful turfgrass establishment fundamentally depends on seed health (Jiang & Su, 2018), especially for cool-season turfgrass species, where seeding is the most common establishment method (Christians et al., 2017). Seed health is primarily determined by germination, vigor, and viability. These essential traits are influenced by several factors, including seed moisture content, seed age, dormancy, storage conditions and duration, and seed handling (Reed et al., 2022). As seeds age, germination percentage, germination speed, longevity, and stress tolerance gradually decline due to cumulative physiological and cellular damage (Kranner, 2013; Zinsmeister et al., 2020). This decline is largely associated with oxidative processes (Walters et al., 2010), which result in the degradation of enzymes (Goel et al., 2003), lipids compromising cellular membranes (Harman & Mattick, 1976), and damage to critical genetic materials such as DNA (El-Maarouf-Bouteau et al., 2011) and RNA (Fleming et al., 2019). This seed damage is defined as “seed deterioration,” an irreversible process influenced by various internal factors, such as seed genetics, and external factors (e.g., air temperature, relative humidity, storage duration, packaging material, oxygen availability, light exposure, and microbial or insect contamination) (Bewley et al., 2013; Kameswara Rao et al., 2017). While seed deterioration is irreversible, its rate can be slowed under proper storage conditions; therefore, it is better to understand what these optimal storage conditions are.

Turfgrass professionals, including sod producers and practitioners, often purchase grass seed in bulk to minimize costs and ensure a consistent supply. It is also common for homeowners

to have leftover grass seed, which they just save for the next growing season. Seed producers face numerous challenges each year, including rising costs of fertilizer, labor, fuel, and equipment replacement or repair, which affect annual seed yields and prices. Some turfgrass professionals store bulk seed to maintain a consistent supply of a specific species or cultivar that is annually produced in small quantities. Another factor is the unpredictable extreme environmental conditions during grass seed production, such as drought, heat, freezing, or other abiotic or biotic stresses, that can severely impact production yields. Turfgrass practitioners may be able to save money and improve maintenance budget planning by anticipating potential grass seed shortages and buying and storing seed when prices are more favorable. However, bulk purchasing requires effective storage practices to preserve seed viability for extended periods. Therefore, a greater understanding of proper long-term storage conditions for turfgrass seed is important for both seed producers and consumers.

In recent years, research (Braun et al., 2023; Carroll et al., 2020; Ebdon & DaCosta, 2020; Larsen & Bibby, 2005; Larsen et al., 2004; Munshaw et al., 2014) has investigated seed morphology, germination characteristics, and responses to optimal and suboptimal sowing temperatures to inform turfgrass practitioners of the best establishment practices. However, if the seed is not properly stored before planting, seed germination percentage may deteriorate, and then the chances for successful turfgrass establishment may drastically decline even if sowing at optimal temperatures. Unfortunately, there has been little research in the last 35 years to investigate the effects of storage conditions and durations on turfgrass seed germination, specifically seed survival, germination and seedling vigor. Past research studies (Mao et al., 2009; Welty et al., 1987) suggested storing seed at cooler temperatures (7 to 10 °C), and approximately 10% moisture content for shorter storage durations to help maintain initial

germination levels. To evaluate germination and seedling vigor, researchers often rely on accelerated aging, a stress-simulation protocol that uses elevated temperatures and extreme relative humidity to artificially catalyze rapid seed deterioration (Park et al., 2022; Zhu et al., 2025). Although this approach shortens the seed deterioration evaluation process, it subjects seeds to conditions far more severe than typical storage environments. Therefore, more research is needed to simulate real-world storage conditions at sod producer farms, golf courses, and other turfgrass facilities to improve our understanding of seed storage practices and educate turfgrass practitioners.

Seed coating has gained attention over the last two decades, with more seed companies incorporating this technology to potentially enhance seed performance. These coatings rely on binders, fillers, and polymers to provide structural integrity and often incorporate active ingredients, such as micronutrients, fungicides, or surfactants, to potentially boost seedling growth (Pedrini et al., 2017). Beyond incorporating hydrogels or water-absorbing polymers to potentially enhance moisture availability in drought-prone environments, these coatings can also include biological agents—such as beneficial microbes—to possibly promote root development and suppress pathogens. While seed coating applies external materials to potentially enhance seed handling, protection, and establishment (Avelar et al., 2012; Pedrini et al., 2020), coated seed is often commercially promoted to boost turfgrass germination and reduce irrigation. Moreover, coatings may directly influence key traits, such as seed viability, longevity, and dormancy—benefits that are already documented in agricultural and vegetable crops (Sohail et al., 2022). Additionally, seed coatings may influence the optimal storage conditions and durations, which are intricately linked to seed viability and longevity (Ma, 2019). Despite the increasing availability of coated turfgrass seed from various companies, more research is needed

to examine the effects of seed coating on germination, seedling emergence, and establishment in turfgrass. Further investigation is necessary to determine whether seed coating can enhance these traits, particularly under various long-term storage conditions. To address these knowledge gaps and provide practical recommendations for improving turfgrass seed storage practices, this study investigated the effects of various long-term storage conditions on the seed germination and viability of coated and noncoated cool-season turfgrass seeds.

Materials and Methods

Experimental design

The experiment was conducted at Kansas State University, Manhattan, KS, from 27 Mar. 2023 to 30 Apr. 2025. Experiment Run 1 and Run 2 were repeated across locations. More specifically, these two experiment runs were conducted during the same timeframe, but storage locations were different to simulate differences in microclimate locations. The experimental design was a two-way factorial arrangement, structured as a 2×3 completely randomized design with four replications. The experiment was repeated over space as mentioned above. Treatment factors included two turfgrass seed coating types (coated and noncoated) and three storage conditions [refrigerator ($\sim 4^{\circ}\text{C}$), indoor ($\sim 22^{\circ}\text{C}$), and non-insulated (i.e., non-climate controlled) shed storage (~ -25 to $\sim 53^{\circ}\text{C}$)]. Turfgrass species investigated included one cultivar of each: tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] (TF), perennial ryegrass (*Lolium perenne* L.) (PR), Kentucky bluegrass (*Poa pratensis* L.) (KB), and strong creeping red fescue (*Festuca rubra* L. ssp. *rubra* Gaudin) (SCRF), which were analyzed separately and not included as a treatment factor. Noncoated and coated (coating with a 1% limestone super-absorbent) turfgrass seed was used of the same cultivar from the same seed

lot of each turfgrass species. The noncoated and coated seed of cultivars used were ‘Raptor III’ tall fescue, ‘Fastball 3GL’ perennial ryegrass, ‘Merit’ Kentucky bluegrass, and ‘Cardinal II’ strong creeping red fescue (Mountain View Seed Company, Salem, OR, USA). Storage conditions included refrigerator ($\sim 4^{\circ}\text{C}$), indoor climate-controlled room temperature ($\sim 22^{\circ}\text{C}$), and a non-insulated shed (reactive to outdoor temperatures and humidity, ranging from ~ -25 to $\sim 53^{\circ}\text{C}$). For Run 1, the three storage locations were at the Rocky Ford Turfgrass Research Center located near the outer perimeter of the city of Manhattan, KS ($39^{\circ} 13' 53''\text{N}$, $96^{\circ} 34' 51''\text{W}$). For Run 2, the three storage locations were in the city of Manhattan, KS ($39^{\circ} 11' 13''\text{N}$, $96^{\circ} 35' 21''\text{W}$). Storage years consisted of 0 years (i.e., baseline measurements for the year when the seed was immediately received) up to 2 years under the above-mentioned storage conditions. Temperature and relative humidity were measured on 1-hour intervals within each storage condition using data loggers (HOBO MX1101, Onset Computer Corp., Bourne, MA, USA). Minimum, maximum, and mean temperature and relative humidity values recorded during the storage period are presented in Tables 3.1 and 3.2.

Approximately 6 g of seed was stored in 15.2-cm coin envelopes for each treatment and replication at the start of the experiment. Treatments were randomized within storage conditions across all years and were held together using rubber bands. For indoor room temperature and refrigerator storage conditions, seed envelopes were placed in their respective locations without a polyester mesh bag. However, for non-insulated shed storage, the seed envelopes were placed together in a polyester mesh bag for ventilation and suspended in the air to prevent rodent feeding damage.

Table 3.1. Minimum, maximum, and mean temperatures recorded under different storage conditions for Run 1 and Run 2.

Run	Storage condition	Temperature (°C)					
		Year 1			Year 2		
		Min	Max	Mean	Min	Max	Mean
Run 1	Indoor	16.8	28.0	22.2	16.8	29.7	22.6
	Refrigerator	−3.5	3.9	0.7	−1.7	4.4	0.6
	Shed	−24.2	44.1	14.2	−23.3	47.6	15.4
	Outdoor environment	−24.2	44.1	13.7	−25.9	39.7	13.0
Run 2	Indoor	18.1	26.7	21.4	18.2	26.2	21.6
	Refrigerator	−1.0	5.2	2.0	0.7	5.4	3.3
	Shed	−20.2	52.5	16.7	−25.3	47.0	16.1
	Outdoor environment	−23.4	43.7	14.0	−25.4	39.4	13.6

Note: Year 1 = Apr. 2023–Mar. 2024; Year 2 = Apr. 2024–Mar. 2025. Outdoor weather data for Runs 1 and 2 were obtained from the Rocky Ford and Manhattan stations, respectively, of the Kansas Mesonet (Manhattan, KS, USA) for comparison purposes only (i.e., not a storage condition).

Table 3.2. Minimum, maximum, and mean relative humidity recorded under different storage conditions for Run 1 and Run 2.

Run	Storage condition	Relative humidity (%)					
		Year 1			Year 2		
		Min	Max	Mean	Min	Max	Mean
Run 1	Indoor	11.3	72.3	43.3	8.8	73.7	43.2
	Refrigerator	18.8	55.0	25.6	14.9	29.7	22.1
	Shed	9.2	99.9	64.4	16.0	99.9	67.5
	Outdoor environment	8.9	99.9	64.5	9.3	99.9	64.3
Run 2	Indoor	11.8	74.3	42.4	11.6	78.9	42.0
	Refrigerator	14.6	61.3	18.3	14.5	49.2	17.7
	Shed	18.9	99.7	55.0	17.7	90.2	54.8
	Outdoor environment	7.8	99.9	63.8	9.1	99.9	61.5

Note: Year 1 = Apr. 2023–Mar. 2024; Year 2 = Apr. 2024–Mar. 2025. Outdoor weather data for Runs 1 and 2 were obtained from the Rocky Ford and Manhattan stations, respectively, of the Kansas Mesonet (Manhattan, KS, USA) for comparison purposes only (i.e., not a storage condition).

Data collection

For all the data variables measured below, initial baseline (i.e., Year 0) measurements were completed prior to placing seed in storage conditions. Then, subsequent measurements were conducted at 1 and 2 years of storage, with the respective seed envelopes collected and brought to the laboratory for data collection.

Seed moisture content

Seed moisture content was measured using the air-oven method following the principles and procedures outlined by the Association of Official Seed Analysts (AOSA) (Association of Official Seed Analysts, 2016). At each storage duration, 5 g of seed from each 6-g envelope was weighed (initial weight) and then placed in separate 15.2 cm paper coin envelopes for drying (Appendix Figure B.1). Seeds were dried for 3 hours at 130 °C in an air-circulating drying oven and then reweighed for dry weight (final weight). Seed moisture content was then calculated as a percentage of the initial sample weight (i.e., fresh weight) using Equation 1 [Eq. 1], according to the procedure outlined by Elias et al. (2012a) and Hay et al. (2023):

$$\text{Seed Moisture Content (\% fresh weight)} = \frac{\text{Initial seed weight (fresh weight, g)} - \text{Final Weight (dry weight, g)}}{\text{Initial seed weight (fresh weight, g)}} \times 100$$

[Eq. 1].

Germination rate and percent

Seed germination tests were conducted according to AOSA principles and procedures (Association of Official Seed Analysts, 2016). All seeds were prechilled at 3–4 °C for over a month before the experiment began. For year 0 (baseline), ~125 seeds for each turfgrass species were placed on blue blotter paper (PBB 325, Hoffman Manufacturing Inc., Corvallis, OR, USA) in a 100 × 15 mm (diameter × height) Petri dish with a lid. Each turfgrass species was replicated four times (i.e., four Petri dishes) for both Runs 1 and 2, totaling 32 Petri dishes per experiment

run (excluding storage conditions and durations for year 0). The blotter paper in the Petri dishes was moistened with 0.2% potassium nitrate (KNO₃) solution throughout the 28-day period as needed. Petri dishes were completely randomized and placed on the non-slip tray and placed in a growth chamber (E15, CM324, Conviron Inc., North Dakota, USA) set to day/night cycle of 25/15 °C with an 8 h day photoperiod. The incubator lights provided a photosynthetic photon flux of ~110 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Germination was monitored and recorded daily over a 28-day period (Appendix Figure B.2). Seeds were considered germinated when both the radicle and coleoptile emerged, after which they were removed from the Petri dishes. After each daily germination check and counts, the Petri dishes were re-randomized and returned to the seed incubator. On the 28th day, the final count of germinated and non-germinated seeds was conducted. Non-viable seeds (moldy) were excluded from the total count. Again, at each storage duration (i.e., year 1 and year 2), ~125 seeds of the remaining 1 g of seed from each 6-g envelope were placed in Petri dishes following the same methods above as year 0, except every treatment was placed in a Petri dish, thus 24 Petri dishes per turfgrass species (2 coating types $\times$ 3 storage conditions $\times$ 4 replications).

For each Petri dish, the total and cumulative germination percentages over time were calculated. The total germination percentage was calculated using Equation [Eq. 2] as described by Beveridge et al. (2020), while the cumulative germination was calculated following the method described by Teveni et al. (2024) in Equation [Eq. 3]:

$$\text{Germination percentage} = \frac{\text{Total seeds germinated}}{\text{Total seeds in petri dish}} \times 100$$

[Eq. 2].

$$\text{Cumulative germination percentage} = \frac{\text{Total seeds germinated by a given day}}{\text{Total seeds in petri dish}} \times 100$$

[Eq. 3].

Using similar methods described by Braun et al. (2023), seed germination speed (i.e., germination vigor) was calculated from cumulative germination percentage over time regressed against days. This analysis was performed using GraphPad Prism (v.10.3, GraphPad Software Inc., CA, USA) and a four-parameter sigmoidal regression model represented by Equation [Eq. 4]:

$$y = \text{Bottom} + \frac{\text{Top} - \text{Bottom}}{1 + \left(\frac{\text{DG}_{50}}{x}\right)^{\text{hillslope}}}$$

[Eq. 4].

where y is the percent germination, Bottom is the y value at the estimated bottom level, Top is the y value at the estimated top level, Taylor is the x value when the response of DG_{50} , which is halfway between Bottom and Top (Days until 50% germination), and Hillslope (no units) describes the slope of the curve at DG_{50} . Days until 50% germination (DG_{50}) were calculated from the regression curves.

Mean germination time (MGT), expressed in days, was calculated for each Petri dish following the methods of Larsen and Andreasen (2004) using Equation [Eq. 5]:

$$\text{MGT} = \frac{\sum n_i d_i}{\sum n_i}$$

[Eq. 5].

where n_i is the number of seeds that germinated in time i (not the accumulated number, but the number correspondent to the i^{th} observation), and d_i is number of days from the beginning of the germination test (incubation period) to the i^{th} observation.

Seedling vigor

Seedling vigor was measured to evaluate the seedling and root growth using the paper towel method (Association of Official Seed Analysts, 1983; Elias et al., 2012b) (Appendix Figure B.3). More specifically, paper germination towels (25 × 38 cm, PG1015, regular weight germination paper, Hoffman Manufacturing Inc., Corvallis, OR, USA) were moistened with tap water, and 20 seeds from the envelope were tested on the germination towel per replication. Seeds were placed 10 cm from the top of the towel and positioned so the radicle would grow toward the base of the towel. Another moistened towel was placed over the seeds on the first towel, and then the towels were rolled, labeled with an indelible pencil and placed in plastic bags. The towel rolls were oriented in plastic buckets to keep towels upright and seeds positioned at the top. Towels were then placed in the same seed incubator, with the same settings used for the germination test above. After 21 days, towels were unrolled, and the shoot and root lengths (mm) of each seedling were measured using a digital caliper (Appendix Figure B.4). Seedlings exhibiting abnormal shoot or root growth (i.e., defects) were not included in counts or mass measurements but were noted. The pooled fresh shoot mass of dissected seedlings that were counted on each towel was weighed and then dried at 60 °C for 72 h, and the pooled dry shoot mass of each treatment was recorded. The average seedling fresh and dry shoot mass (grams) was calculated by dividing the total mass by the number of seedlings dissected for each treatment.

Data analysis

Data from each year were analyzed using analysis of variance (ANOVA) in SAS 9.4 (SAS Institute Inc., Cary, NC) with the GLIMMIX procedure to test main effects and interactions within each turfgrass species. Treatments were treated as fixed effects, and

replication (block) as a random effect. Residual normality was checked using the Shapiro–Wilk test (Shapiro & Wilk, 1965). Sigmoidal regression and correlation analyses were conducted using GraphPad Prism (v.10.3, GraphPad Software, San Diego, CA). Means were separated using Fisher’s protected LSD test at $\alpha = 0.05$ when F -tests were significant ($P \leq 0.05$).

To evaluate relationships among seed quality parameters across all long-term storage observations, Pearson correlation analysis (r) was conducted in R (version 4.4.2) using the *Hmisc* package. Parameters included seed moisture content, germination percentage, top germination percentage, mean germination time, days to 50% germination (DG50), average shoot dry weight, shoot length, and root length. Statistical significance was determined at $P < 0.05$, $P < 0.01$, and $P < 0.001$. Correlation analysis was used as a complementary approach to summarize overall relationships among seed quality traits and to support interpretation of treatment effects.

Results

Storage environment

Temperature and relative humidity varied among storage conditions and experimental runs (Tables 3.1 and 3.2). Refrigerator storage maintained the coolest and most stable temperatures across both runs and years, with temperatures ranging from -3.5 to 5.4 °C and mean temperatures from 0.6 to 3.3 °C. Indoor storage was also relatively stable, with mean temperatures ranging from 21.4 to 22.6 °C. In contrast, shed and outdoor environments had the widest temperature ranges, exposing seeds to both freezing and high-temperature conditions. Shed storage showed the greatest temperature fluctuation, ranging from -25.3 to 52.5 °C, whereas outdoor air temperatures ranged from -25.9 to 44.1 °C. Indoor and refrigerator storage conditions were generally similar between Run 1 and Run 2; however, shed storage differed

more between runs. Mean shed temperatures in Run 2 exceeded those of Run 1 by 2.5 °C in Year 1 and 0.7 °C in Year 2. These temperature differences between runs are primarily attributed to the structural design and ventilation capacity of the storage facilities. The door of the shed used for Run 1 were slightly open (i.e., gap between the doors, not sealed shut), which facilitated passive ventilation and greater air exchange. Conversely, the storage shed in Run 2 was more enclosed, promoting thermal retention that drove up baseline averages and resulted in a peak recorded temperature of 52.5 °C (Table 3.1).

Relative humidity also differed among storage conditions and runs (Table 3.2). Indoor storage had the most consistent mean relative humidity, ranging from 42.0 to 43.3% across both runs and years. In contrast, the shed storage environment, and outdoor environments for comparison, had the widest range of relative humidity, with maximum values near or equal to 99%, indicating periods of the highest amount of water vapor it can hold at its current temperature. Mean relative humidity in the shed and outdoor environments was generally higher than in the indoor and refrigerator storage, ranging from 54.8 to 67.5% for the shed storage and from 61.5 to 64.5% for the outdoor environment. Compared with Run 1, mean relative humidity in shed storage was lower in Run 2, dropped by 15% in Year 1 and 19% in Year 2. This drop directly mirrors the temperature data: the enclosed design and warmer temperatures of the Run 2 shed naturally lowered the surrounding relative humidity compared to the more open, ventilated structure of Run 1. For comparison, outdoor mean relative humidity followed a similar pattern, with Run 2 being slightly lower than Run 1 in both years (Table 3.2). Overall, shed storage exposed seeds to the greatest environmental fluctuations of temperature and moisture, whereas indoor and refrigerator storage provided more stable storage conditions.

Seed moisture content

A significant coating $\times$ storage condition interaction was observed for seed moisture content across all species in both years of Run 1 and Run 2 (Figure 3.1; Tables 3.3 and 3.4; Appendix Tables B.1 and B.2). Year 0, representing the initial seed moisture prior to storage, interaction effects were not evaluated due to no storage condition treatments imposed yet. However, a consistent coating effect was observed across all species in both runs, with noncoated seed exhibiting higher seed moisture content (7.0 to 8.6%) than coated seed (2.1 to 4.7%) (Tables 3.3 and 3.4). Thus, the coated seed began the experiment with lower seed moisture content levels due to the coating process. In Year 1, noncoated seed stored under shed conditions exhibited the highest moisture content across all species, ranging from 10.4 to 10.8% in Run 1 and 8.5 to 9.0% in Run 2. This was likely due to the seed being more exposed to higher-relative-humidity environments during storage. The coated seed stored under the same shed conditions did not exhibit a consistent increase in seed moisture content compared with the noncoated seed, indicating a protective coating effect. Both the coated and noncoated seed stored under indoor and refrigerated conditions for 1 yr in both runs maintained lower seed moisture content (2.3 to 4.3% in coated seed) and (7.6 to 8.2% in noncoated seed), which was similar to the baseline (Year 0) measurements for each respective coating or noncoated treatment

By Year 2, coating $\times$ storage condition interactions remained evident across runs (Figure 3.1). In Run 1, both noncoated and coated seeds stored under shed conditions exhibited lower seed moisture content compared with Year 1 but noncoated seeds still remained higher (6.7 to 7.7%) than coated seeds under the same conditions (1.8 to 3.9%) across species. However, in Run 2, noncoated seed, and at times coated seed, stored under shed conditions exhibited increased seed moisture content relative to Year 1, ranging from 9.7 to 10.8% across species.

Coated seed under the same conditions continued to maintain lower seed moisture contents (3.1 to 5.6%) than noncoated seed but also exhibited a slight increase in Year 2 in Run 2. Overall, both noncoated and coated seed stored under refrigerated and indoor conditions maintained relatively stable seed moisture levels than non-insulated shed storage across both runs; however, coated seed maintained consistently lower seed moisture content compared with noncoated across all storage conditions (Figure. 3.1; Appendix Tables B.1 and B.2).

From Year 1 to Year 2, seed moisture content in Run 1 generally decreased across storage conditions, with noncoated seed under shed storage declining by 29 to 36% across species. In contrast, Run 2 exhibited increases in moisture content for noncoated seed under shed storage (15 to 22%). Across both runs, coated seed consistently maintained approximately 45 to 72% lower seed moisture content and exhibited reduced variability compared with noncoated seed. Species differences were minimal; however, KB consistently exhibited lower absolute seed moisture content compared with other species (Tables 3.3 and 3.4). Across storage environments, refrigerated conditions yielded the lowest moisture content in noncoated seed, whereas shed storage produced the highest and most variable seed moisture content levels. The coated seed maintained a lower seed moisture content and less variability across all storage conditions.

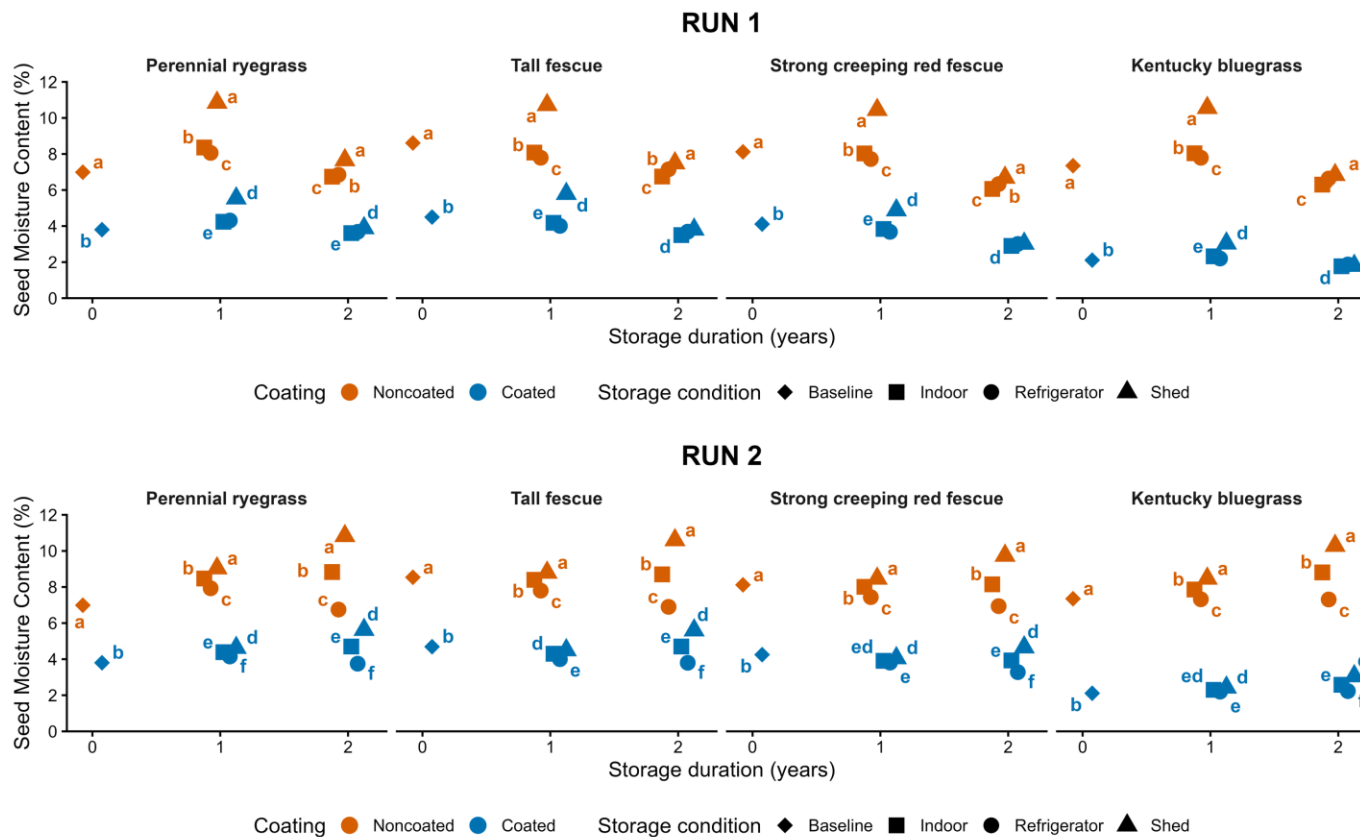


Figure 3.1. Interaction effects of coating $\times$ storage condition on seed moisture content (%) across storage durations in four cool-season turfgrass species (Run 1 – Top and Run 2 – Bottom). Note: Year 0 represents baseline seed moisture content prior to storage and is not included in the coating $\times$ storage condition interaction analysis, instead it is the coating main effect for Year 0 shown in the figure. Points represent treatment means for each species, year, and storage condition. Means followed by different letters are significantly different according to Fisher's protected LSD test ($P \leq 0.05$) within each species and each year.

Table 3.3. Effects of coating and storage condition on seed moisture content (%) of cool-season turfgrass species across years in Run 1.

	Seed moisture content (%)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	3.8 b	4.7 b	3.7 b	4.5 b	4.7 b	3.7 b	4.1 b	4.1 b	3.0 b	2.1 b	2.5 b	1.8 b
Noncoated	7.0 a	9.1 a	7.1 a	8.6 a	8.9 a	7.1 a	8.1 a	8.7 a	6.4 a	7.3 a	8.8 a	6.6 a
Storage condition												
Indoor	5.4	6.3 b	5.2 c	6.5	6.1 b	5.1 c	6.1	5.9 b	4.5 c	4.7	5.2 b	4.0 b
Refrigerator	–	6.2 b	5.3 b	–	5.9 c	5.4 b	–	5.7 c	4.7 b	–	5.0 b	4.3 a
Shed	–	8.2 a	5.8 a	–	8.3 a	5.6 a	–	7.7 a	4.9 a	–	6.8 a	4.3 a
<i>p</i> values												
Coating	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0002	<.0001	<.0001	0.0001	<.0001	<.0001
Storage condition	–	<.0001	<.0001	–	<.0001	<.0001	–	<.0001	0.0001	–	<.0001	<.0001
Coating × Storage condition	–	<.0001	<.0001	–	<.0001	0.0038	–	<.0001	0.0040	–	<.0001	0.0003

Note: Means within a column for each main effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($P \leq 0.05$). Year 0 represents baseline seed moisture content prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table 3.4. Effects of coating and storage condition on seed moisture content (%) of cool-season turfgrass species across years in Run 2.

	Seed moisture content (%)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	3.8 b	4.4 b	4.7 b	4.7 b	4.3 b	4.7 b	4.2 b	3.9 b	4.0 b	2.1 b	2.3 b	2.6 b
Noncoated	7.0 a	8.5 a	8.8 a	8.5 a	8.3 a	8.7 a	8.1 a	8.0 a	8.3 a	7.3 a	7.9 a	8.8 a
Storage condition												
Indoor	5.4	6.4 b	6.8 b	6.6	6.4 b	6.7 b	6.2	6.0 b	6.0 b	4.7	5.2 b	5.7 b
Refrigerator	–	6.0 c	5.2 c	–	5.9 c	5.4 c	–	5.6 c	5.1 c	–	4.8 c	4.8 c
Shed	–	6.8 a	8.2 a	–	6.6 a	8.1 a	–	6.3 a	7.2 a	–	5.4 a	6.7 a
<i>p</i> values												
Coating	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0002	<.0001	<.0001	0.0001	<.0001	<.0001
Storage condition	–	<.0001	<.0001	–	<.0001	<.0001	–	<.0001	<.0001	–	<.0001	<.0001
Coating × Storage condition	–	<.0001	<.0001	–	0.0007	<.0001	–	0.0002	<.0001	–	<.0001	<.0001

Note: Means within a column for each main effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($P \leq 0.05$). Year 0 represents baseline seed moisture content prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–)

Germination

Across both runs, baseline (Year 0) germination percentages across all four species were >90% for PR and 80 to 94% for TF, KB, and SCRF (Tables 3.5 and 3.6). Then, a significant coating $\times$ storage condition interaction was observed for TF in Year 1 (Run 1) and for TF and KB in both years in both Runs 1 and 2, indicating that coating effects were species- specific and depended on storage environment (Tables 3.5 and 3.6; Figures. 3.2 and 3.3). In Year 1, germination remained high (i.e., 80 to 95%) across most treatments in both runs for both TF and KB. However, in Run 1, germination decreased under shed storage, particularly for noncoated TF seed, where germination declined to 66% compared with 85% for coated TF seed. In KB, germination of noncoated seed under shed storage was lower (75 to 78% germination) compared with indoor and refrigerated conditions, with minimal differences between coating treatments (Figure. 3.2; Appendix Table B.3). A similar trend was observed in Run 2, where noncoated TF showed lower germination (83%) compared with coated seed (94%) under shed storage conditions after 1 yr, indicating some benefits of coating under fluctuating conditions. In contrast, noncoated KB seed had higher germination than coated seed under the same shed conditions. By Year 2, interaction effects became more pronounced across both runs. In Run 1, although germination declined under shed conditions, no significant interaction was observed in TF due to greater variability among treatments. However, coated KB exhibited greater germination (40%) compared with noncoated seed (29%) under shed conditions, indicating an advantage of coating. Regardless of coating, the highest germination was maintained under refrigerated and indoor conditions, ranging from 75 to 88% (Figure. 3.2; Appendix Table B.3). In Run 2, significant interaction was found in TF and KB. Refrigerated storage maintained high germination in both species regardless of coating, with TF remaining above 90% and KB above

86%, indicating no coating effects under optimal storage conditions. Indoor storage resulted in a slight decline in germination (3–23%) relative to refrigerated conditions, with noncoated seed exhibiting slightly higher germination than coated seed across both species (Figure. 3.3; Appendix Table B.4).

Overall, shed storage caused the greatest germination losses, especially in Run 1, where TF and KB declined by 80% and 55%, respectively, from Year 1 to Year 2. In Run 2, losses were smaller, with TF and KB declining by 24% and 13%, respectively, whereas germination under indoor and refrigerated storage remained relatively stable across both runs ($\leq 12\%$; Appendix Tables B.3 and B.4). There were no significant coating $\times$ storage interactions observed in PR and SCRF, indicating species-specific responses (Tables 3.5 and 3.6). Across both runs, storage condition was the primary factor influencing germination in all species, whereas coating effects were present but relatively small. Daily weather extremes likely had a greater influence on the shed storage conditions of Run 1 compared with Run 2, which is evident with the larger decrease in overall germination percentage in each species in Years 1 and 2 compared with Run 2. Still, the shed storage conditions in Run 2 had a negative impact on germination compared with the more optimal refrigerator or climate-controlled indoor conditions.

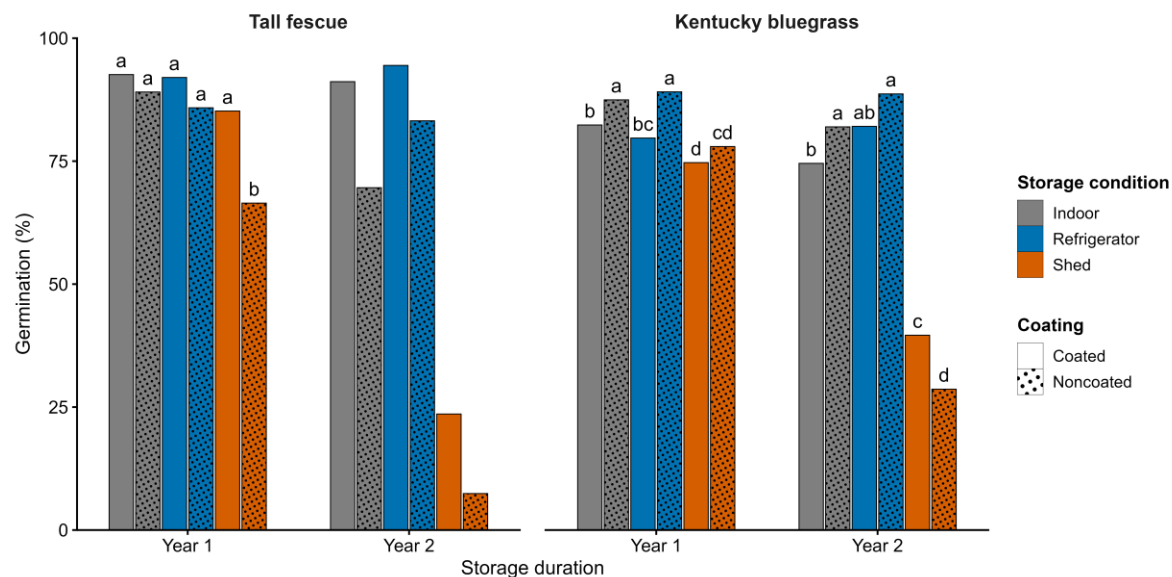


Figure 3.2. Effect of coating $\times$ storage condition interaction on germination (%) of coated and noncoated tall fescue and Kentucky bluegrass across storage durations (Run 1).
Note: Bars represent mean germination percentages for each treatment combination. Coated and noncoated indicate seed coating treatments. Indoor, refrigerator, and shed denote storage conditions. Means within a storage duration and species followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test ($P \leq 0.05$).

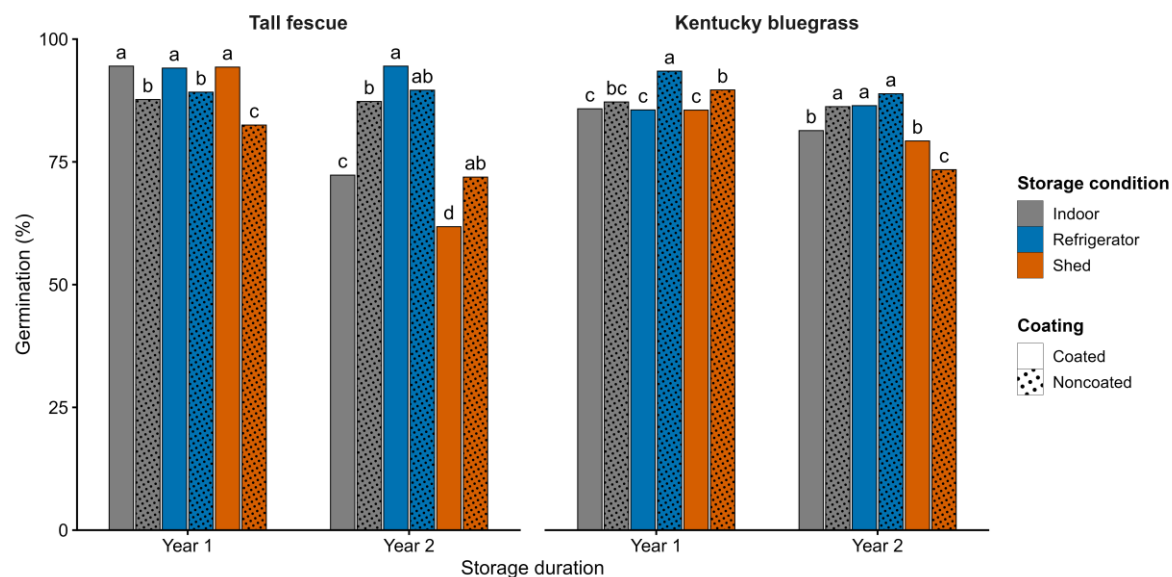


Figure 3.3. Effect of coating $\times$ storage condition interaction on germination (%) of coated and noncoated tall fescue and Kentucky bluegrass across storage durations (Run 2). Means within a storage duration and species followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test ($P \leq 0.05$). *Note:* See Figure 2 for a description of treatments and statistical comparisons.

Table 3.5. Effects of coating and storage condition on germination (%) of cool-season turfgrass species across years in Run 1.

	Germination (%)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	96.9	93.2 a	87.5 a	93.7 a	89.9 a	69.7 a	85.4 a	69.6	50.1	84.1	78.9 b	65.4
Noncoated	91.2	88.5 b	82.9 a	80.6 b	80.5 b	53.4 b	80.1 b	66.9	47.2	83.8	84.8 a	66.4
Storage condition												
Indoor	94.1	92.2	90.5 a	87.2	90.8 a	80.4 b	82.7	79.9 a	67.7 b	83.9	84.9 a	78.3 b
Refrigerator	–	90.6	92.2 a	–	88.9 a	88.8 a	–	82.5 a	76.7 a	–	84.4 a	85.4 a
Shed	–	89.7	72.9 b	–	75.8 b	15.5 c	–	42.4 b	1.6 c	–	76.3 b	34.1 c
<i>p</i> values												
Coating	0.0815	0.0008	0.0048	0.0004	0.0004	<.0001	0.0466	0.1418	0.2702	0.9106	<.0001	0.6980
Storage condition	–	0.2251	<.0001	–	<.0001	<.0001	–	<.0001	<.0001	–	<.0001	<.0001
Coating × Storage condition	–	0.1609	0.1256	–	0.0224	0.1869	–	0.5714	0.1521	–	0.0454	0.0168

Note: Means within a column for each main effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($P \leq 0.05$). Year 0 represents baseline germination percentage prior to storage treatment; storage conditions were not applicable, as indicated by a dash (–).

Table 3.6. Effects of coating and storage condition on germination (%) of cool-season turfgrass species across years in Run 2.

	Germination (%)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	96.5 a	94.1 a	93.8 a	93.4 a	94.3 a	76.2 b	85.4 a	82.1 a	55.6 a	86.6	85.6 b	82.4
Noncoated	91.4 b	89.5 b	86.5 b	82.9 b	86.4 b	82.9 a	80.1 b	76.5 b	50.1 b	87.1	90.1 a	82.8
Storage condition												
Indoor	93.9	91.9 ba	92.3 a	88.1	91.1 a	79.8 b	82.7	81.7 a	63.3 a	86.9	86.5	83.8 b
Refrigerator	–	93.4 a	90.9 a	–	91.7 a	92.0 a	–	80.7 a	67.6 a	–	89.5	87.7 a
Shed	–	90.1 b	87.3 b	–	88.4 b	66.8 b	–	75.6 b	27.5 b	–	87.6	76.3 c
<i>p</i> values												
Coating	0.0065	<.0001	<.0001	0.0312	<.0001	0.0205	0.0466	0.0011	0.0415	0.8711	0.0003	0.7169
Storage condition	–	0.0073	0.0023	–	0.0334	<.0001	–	0.0054	<.0001	–	0.0611	<.0001
Coating × Storage condition	–	0.0815	0.8316	–	0.0316	0.0178	–	0.1838	0.0796	–	0.0445	0.0113

Note: Means within a column for each main effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($P \leq 0.05$). Year 0 represents baseline germination percentage prior to storage treatment; storage conditions were not applicable, as indicated by a dash (–).

Germination speed

Germination speed was assessed using mean germination time (MGT) and days to 50% germination (DG₅₀) and a sigmoidal regression model (Appendix Tables B.5, B.6, B.7, and B.8). As expected, similar trends were observed across these two parameters since they are measuring the same response variable; therefore, only MGT will be discussed. A significant coating × storage condition interaction was observed for MGT; however, interactions were inconsistent across species, years, and runs (Tables 3.7 and 3.8).

In both Runs, the highest MGT values (i.e., slower germination speeds) were more often observed with seeds stored in the non-insulated shed conditions, regardless of coating (Tables 3.7 and 3.8). However, there were many instances within each species in which neither coating nor storage condition affected germination speed. When differences did occur within species, refrigerator storage conditions, and at times indoor storage conditions, most often exhibited seed with the faster germination speeds (lowest MGT values). Overall, neither coated nor noncoated seed consistently had lower MGT values, but storage condition was the primary factor influencing MGT, with shed storage consistently resulting in higher MGT (slower germination) compared with indoor and refrigerated conditions across species (Appendix Tables B.5 and B.6). Days to 50% germination (DG₅₀) followed trends similar to MGT across treatments (Appendix Tables B.7 and B.8).

Table 3.7. Interaction effects of coating $\times$ storage condition on mean germination time (days) of cool-season turfgrass species across years in Run 1.

Coating $\times$ Storage condition	Mean Germination Time (days)							
	Perennial ryegrass		Tall fescue		Strong creeping red fescue		Kentucky bluegrass	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Coated $\times$ Indoor	5.9 c	6.7 cd	8.3	10.5	8.2 cb	9.5	9.3	9.4 dc
Coated $\times$ Refrigerator	6.2 cb	6.5 d	8.7	9.2	8.5 b	9.3	10.1	9.0 d
Coated $\times$ Shed	6.5 b	8.5 a	10.1	13.3	10.3 a	7.4	11.0	15.5 a
Noncoated $\times$ Indoor	6.0 c	7.0 c	9.3	11.4	7.9 c	9.0	9.3	10.1 c
Noncoated $\times$ Refrigerator	7.1 a	8.0 b	9.6	11.1	7.9 c	8.7	8.9	9.7 dc
Noncoated $\times$ Shed	6.6 b	8.1 ba	11.2	14.7	8.6 b	11	10.7	12.9 b
<i>P-values</i>								
Coating $\times$ Storage condition	0.0078	<.0001	0.9678	0.5032	0.0081	0.4608	0.1448	<.0001

Note: Means within a column followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded p values indicate statistical significance ($P \leq 0.05$). Smaller values for mean germination time (MGT) indicate faster germination speeds.

Table 3.8. Interaction effects of coating $\times$ storage condition on mean germination time (days) of cool-season turfgrass species across years in Run 2.

Coating $\times$ Storage condition	Mean Germination Time (days)							
	Perennial ryegrass		Tall fescue		Strong creeping red fescue		Kentucky bluegrass	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Coated $\times$ Indoor	5.4	6.8	8.9	10.5 c	8.3	10.0	9.7	10.3 b
Coated $\times$ Refrigerator	5.6	7.2	8.7	9.6 d	9.0	10.1	10.3	10.5 b
Coated $\times$ Shed	5.6	7.3	8.7	12.4 a	8.7	12.9	10.3	12.2 a
Noncoated $\times$ Indoor	5.9	7.1	10.5	11.5 b	8.2	10.3	9.5	10.1 cb
Noncoated $\times$ Refrigerator	5.9	7.8	10.2	11.8 ba	8.5	10.4	9.4	9.4 c
Noncoated $\times$ Shed	5.9	7.4	11.4	12.2 ba	8.6	12.3	9.7	10.1 cb
<i>P-values</i>								
Coating $\times$ Storage condition	0.5146	0.3816	0.1307	0.0026	0.4946	0.3358	0.1472	0.0088

Note: Means within a column followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded p values indicate statistical significance ($P \leq 0.05$). Smaller values for mean germination time (MGT) indicate faster germination speeds

Seedling vigor

Seedling vigor, assessed using shoot and root lengths, showed species-specific responses, with limited coating $\times$ storage condition interactions across both runs (Tables 3.9 and 3.10; Appendix Tables B.9, B.10, B.11 and B.12). In Run 1, a coating $\times$ storage condition interaction for shoot length was observed in TF in Year 2 and KB in Year 1 (Tables 3.9 and 3.10). In TF (Year 2), coated seed stored under indoor (72.5 mm) and refrigerated (65.2 mm) conditions produced greater shoot length compared with coated seed stored in the shed (54.1 mm), representing a reduction of 25% under shed conditions. Noncoated treatments ranged from 61.3 to 66.9 mm across storage conditions and were not consistently different from coated seed, except for noncoated seed stored in a refrigerator. In KB (Year 1), noncoated seed stored in a refrigerator and coated seed stored indoors produced the greatest shoot length (35.3 to 35.4 mm), which was similar to the noncoated $\times$ indoor and coated $\times$ shed treatments. Overall variation among treatments was limited, with values differing by up to approximately 16% across storage conditions (Table 3.10). No interaction effects were observed in PR and SCRF in Run 1.

In Run 2, significant interactions were observed in TF in Year 1 and SCRF in Year 2 (Tables 3.9 and 3.10). In TF (Year 1), coated seed stored indoors produced greater shoot length (73.9 mm) than noncoated seed stored indoors (59.6 mm), representing an approximately 17% reduction in noncoated seed, and greater shoot length than coated seed stored in a refrigerator (65.5 mm). In SCRF (Year 2), coated seed stored indoors produced greater shoot length (53.5 mm) than other treatments except for coated seed stored in a refrigerator. No interaction effects were observed in PR or KB in Run 2.

Across runs and species, storage conditions exerted a stronger and more consistent influence on seedling vigor as indicated by shoot lengths recorded after 21 d. Shed storage

reduced shoot length relative to indoor and refrigerated conditions, with reductions of up to 14%, most evident in Year 2. However, both storage and coating effects on shoot length were inconsistent and species dependent. In Year 2 of Run 1, shed storage resulted in the complete absence of seedling emergence in SCRF, indicating loss of seed viability under this condition (Appendix Table B.9). This finding aligns with the low (1.9%) germination percentage observed with shed storage conditions in SCRF in Year 2 in Run 1.

Root length followed similar trends as shoot length measurements (Table 3.11; Appendix Tables B.11 and B.12). However, no significant coating $\times$ storage condition interaction was observed with root lengths across species or runs, indicating largely independent effects. Coating responses were species-specific: coated PR and TF produced longer roots than noncoated seed in both runs, whereas KB showed the opposite pattern (i.e., noncoated seed with greater root lengths). Coating did not improve root length in SCRF. Across species, shed storage resulted in shorter root length compared with indoor and refrigerated conditions. In Year 2 of Run 1, shed storage resulted in the complete absence of seedling emergence in SCRF, indicating that seed viability was lost under shed conditions as storage duration increased as previously mentioned above (Appendix Table B.9).

Overall, storage conditions exerted a stronger and more consistent effect on seedling vigor, compared with coating treatments, indicated by shoot and root lengths, than coating, with shed storage reducing both shoot and root length across species and years. Coating effects were variable and species-dependent, with the most consistent responses observed in TF.

Table 3.9. ANOVA for main effects (coating and storage condition) and their interaction on shoot length (mm) of cool-season turfgrass species across years in both Runs 1 and 2.

	Shoot length (mm)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
<i>p</i> values	RUN 1											
Coating	0.4330	0.0711	0.0162	0.1005	0.0044	0.7994	0.8962	0.2398	0.0064	0.9233	0.8616	0.0502
Storage condition	–	0.5958	0.1057	–	0.3304	0.0390	–	0.6855	0.3550	–	0.0879	0.0416
Coating × Storage condition	–	0.7911	0.3978	–	0.6618	0.0421	–	0.3093	0.4876	–	0.0128	0.8973
	RUN 2											
Coating	0.2446	0.0520	0.0181	0.2251	0.0352	<.0001	0.1469	0.5817	0.3583	0.5224	0.9629	0.2226
Storage condition	–	0.3085	<.0001	–	0.1244	0.0011	–	0.6051	0.0445	–	0.3563	0.0110
Coating × Storage condition	–	0.8709	0.6471	–	0.0001	0.9226	–	0.8374	0.0003	–	0.4274	0.8973

Note: P-values represent the effects of coating, storage condition, and their interaction (coating × storage condition) for each species and storage duration. Bolded *p* values indicate statistical significance ($P \leq 0.05$). Year 0 represents baseline measurements prior to storage; therefore, storage condition and coating × storage condition effects were not applicable.

Table 3.10. Interaction effects of coating $\times$ storage condition on shoot length (mm) of cool-season turfgrass species across years in Runs 1 and 2.

Coating $\times$ Storage condition	Shoot length (mm)							
	RUN 1				RUN 2			
	Tall fescue		Kentucky bluegrass		Tall fescue		Strong creeping red fescue	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Coated $\times$ Indoor	72.3	72.4 a	35.3 a	31.6	73.9 a	67.3	50.5	53.5 a
Coated $\times$ Refrigerator	74.3	65.2 a	30.7 b	31.4	65.5 b	77.9	48.8	50.1 ba
Coated $\times$ Shed	75.3	54.1 b	33.0 ba	27.6	70.5 ba	68.3	50.9	43.1 d
Noncoated $\times$ Indoor	64.4	61.5 ba	33.4 ba	33.4	59.6 c	54.0	50.7	45.2 dc
Noncoated $\times$ Refrigerator	70.1	66.9 a	35.4 a	34.5	70.4 ba	66.7	47.8	49.1 bc
Noncoated $\times$ Shed	66.7	61.3 ba	29.7 b	30.5	70.3 ba	56.2	48.4	49.3 b
<i>p values</i>								
Coating $\times$ Storage condition	0.6618	0.0421	0.0128	0.8973	0.0001	0.9226	0.8374	0.0003

Note: Means within a column followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($P \leq 0.05$). Values represent mean shoot length (mm) for each coating $\times$ storage condition combination. Only species with significant coating $\times$ storage condition interactions are presented.

Table 3.11. ANOVA for main effects (coating and storage condition) and their interaction on root length (mm) of cool-season turfgrass species across storage durations in Run 1 and Run 2.

	Root length (mm)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
<i>p</i> values	RUN 1											
Coating	0.4196	0.0983	0.0144	0.0920	<.0001	0.0928	0.4381	0.4880	0.5595	0.9093	0.5965	0.0007
Storage condition	–	0.0031	0.3083	–	0.0468	0.1838	–	0.6857	0.0204	–	0.3187	0.1820
Coating × Storage condition	–	0.2491	0.2300	–	0.5554	0.3448	–	0.7750	0.3393	–	0.1106	0.5331
	RUN 2											
Coating	0.0146	0.7947	0.7932	0.2613	0.0181	<.0001	0.2772	0.1403	0.5611	0.4311	<.0001	0.0004
Storage condition	–	0.7547	0.2183	–	0.4936	0.0519	–	0.4817	0.1700	–	0.0029	0.2947
Coating × Storage condition	–	0.4193	0.8948	–	0.0878	0.0500	–	0.1833	0.6858	–	0.3611	0.6519

Note: P-values represent the effects of coating, storage condition, and their interaction (coating × storage condition) for each species and storage duration. Bolded *p* values indicate statistical significance ($P \leq 0.05$). Year 0 represents baseline measurements prior to storage; therefore, storage condition and coating × storage condition effects were not applicable.

Pearson correlation analysis

Pearson correlation analysis revealed strong relationships among germination, germination speed, and seedling vigor traits across all long-term storage conditions (Figure 3.4). Germination percentage was positively correlated with top germination percentage ($r = 1.00$), average seedling dry weight ($r = 0.24$), shoot length ($r = 0.24$), and root length ($r = 0.31$). Germination was negatively correlated with MGT ($r = -0.60$) and DG_{50} ($r = -0.58$), indicating that higher germination was associated with faster germination. MGT and DG_{50} were almost perfectly correlated ($r = 1.00$), whereas shoot length, root length, and average seedling dry weight were strongly and positively associated ($r = 0.77$ – 0.92). Seed moisture content exhibited weak correlations with all measured seed quality traits ($|r| \leq 0.14$).

Additional parameters

Additional parameters, including Hillslope, Top (%), and seedling average fresh and dry weight, showed minimal or inconsistent treatment effects across runs and species. Therefore, results are presented in Appendix Tables B.13–B.20.

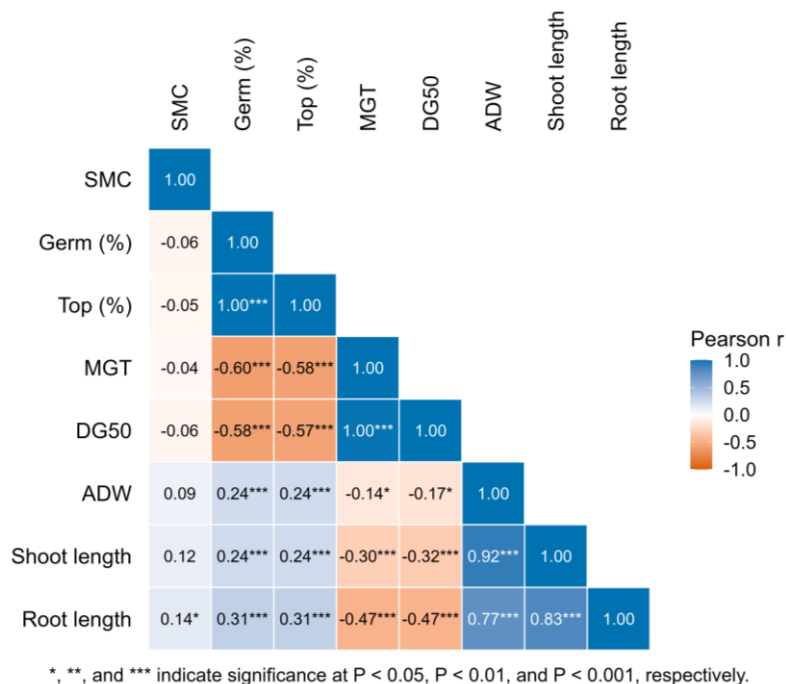


Figure 3.4. Pearson correlation matrix among seed moisture content, germination, germination speed, and seedling growth traits in the long-term storage experiment, pooled across both runs and all species. *Note:* SMC, seed moisture content (%); Germ, germination (%); Top, top germination percentage (%); MGT, mean germination time (d); DG₅₀, days to 50% germination (d); ADW, average seedling dry weight (mg); Shoot length (cm); Root length (cm). Values shown are Pearson correlation coefficients (r). Blue and orange colors indicate positive and negative correlations, respectively, with darker colors representing stronger relationships. Only the lower triangle of the correlation matrix is displayed. *, **, and *** indicate statistical significance at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

Discussion

Seed moisture content

Seed moisture content was consistently lower in coated seed compared with noncoated seed across all species, storage conditions, and durations, with seed moisture content measurements ranging from 45 to 72% lower in coated compared with noncoated seed. This difference is attributed to lower initial moisture content in coated seed, likely resulting from the coating process, which includes slurry application followed by drum or forced-air drying

(Pedrini et al., 2017; Taylor et al., 1998). In addition, coating materials may alter seed–environment interactions by acting as semi-permeable barriers that restrict moisture exchange, thereby reducing variability in seed moisture content across storage conditions (Jacob et al., 2016; Pedrini et al., 2020; Taylor et al., 1997).

The significant coating $\times$ storage condition interaction observed across both runs in all species indicates the strong influence of ambient storage conditions on seed moisture content. Noncoated seed stored under shed conditions exhibited the greatest moisture content, likely due to greater exposure to fluctuating temperatures and relative humidity, resulting in repeated cycles of moisture adsorption and desorption. These responses are consistent with seed storage principles, indicating that temperature and relative humidity govern equilibrium moisture content and seed longevity (Ellis & Roberts, 1980; Harrington, 1972; Hay et al., 2023; Ma, 2019; Walters et al., 2010). In contrast, refrigerated and indoor storage maintained lower, more stable moisture content, regardless of coating, demonstrating how controlled environments mitigate the moisture fluctuations common in non-insulated storage (shed). Cool, stable conditions limit moisture exchange and metabolic activity, thereby preserving seed quality during storage (Bewley et al., 2013; Hay et al., 2023; Zinsmeister et al., 2020). Similar trends have been reported in turfgrass species, where reduced storage temperatures of 10 °C improved seed longevity (Welty et al., 1987).

The buffering effect of the coating was most evident under shed storage conditions, where the coated seed maintained a relatively stable moisture content despite environmental fluctuations. This suggests that the coating matrix restricted moisture vapor transmission between the seed and the surrounding air. This response is particularly important under non-insulated storage, where elevated seed moisture content accelerates metabolic activity, oxidative

damage, and microbial growth, ultimately reducing seed viability (Bewley et al., 2013; Harrington, 1972).

Differences between Run 1 and Run 2 under shed storage further emphasize the influence of storage micro-environments on seed moisture content. Run 1 shed storage had a lower mean temperature but higher relative humidity, whereas Run 2 shed storage had a higher mean temperature but lower relative humidity during Years 1 and 2. These contrasting patterns suggest that seed moisture content was influenced by the combined effects of temperature and relative humidity rather than temperature alone. Noncoated seed was more sensitive to these environmental changes, whereas coated seed maintained lower, more stable moisture content across runs, likely because the coating matrix reduced moisture exchange with the surrounding environment (Jacob et al., 2016). The range of seed moisture content values among species was similar; however, KB consistently exhibited lower moisture content values relative to other species. This response may be associated with differences in seed morphology (i.e., size and shape) and seed coat permeability, which influence moisture exchange dynamics (Bewley et al., 2013).

Overall, the storage environment, through its associated temperature and relative humidity conditions, was the primary factor influencing seed moisture content, while seed coating provided an additional level of protection under variable conditions. These differences are expected to influence germination and seed viability, as discussed in subsequent sections.

Germination

Germination responses were driven by storage environments, while coating effects were present but smaller and varied among species. Declines in germination percentage under shed storage conditions corresponded to elevated seed moisture content in noncoated seed, indicating

that storage moisture conditions (i.e., relative humidity) and air temperatures influenced seed viability. Increased seed moisture content accelerates metabolic activity and promotes oxidative damage, ultimately leading to membrane deterioration and reduced germination (Bewley et al., 2013; Harrington, 1972; Hay et al., 2023; Walters et al., 2005). These higher seed moisture contents were evident with seed stored in non-insulated shed conditions but also with noncoated seed having higher seed moisture content at the start of the experiments (baseline measurements). Reductions in germination under shed conditions, particularly in Run 1, likely reflect the combined effects of high and fluctuating temperatures and relative humidity. These conditions promote repeated cycles of moisture adsorption and desorption, accelerating seed aging and deterioration (Maleki Farahani et al., 2025; Probert et al., 2009). This response was evident in TF and KB, where germination declined from Year 1 to Year 2. In contrast, the relatively stable germination observed under refrigerated and indoor storage conditions aligns with the lower, more stable seed moisture content maintained in these environments, reinforcing the importance of environmental control in preserving seed viability (Ellis & Roberts, 1980; Walters et al., 2010).

Coating effects were most evident under shed storage but also observed as the main effect in multiple species. Coated seed more often maintained higher germination than noncoated seed, indicating a protective effect under unfavorable conditions. This response is consistent with the lower variability in seed moisture content observed in coated seed, suggesting that coatings limit moisture exchange between the seed and the surrounding environment. However, under optimal storage environments (refrigerated and indoor), coating effects were minimal, as germination remained high regardless of coating or no coating, indicating that storage conditions outweighed any potential benefits of coating.

Species-specific differences were observed. The limited interaction in PR and SCRF may suggest that these species were less sensitive to the effects of coating, whereas TF and KB showed greater differences due to coating under the storage conditions. These differences may be associated with variation in seed morphology, seed coat permeability, and inherent storage tolerance among species (Bewley et al., 2013).

Overall, storage conditions were the primary factor influencing germination during storage, with seed moisture content acting as a key driver. Seed coating provided additional protection under variable, suboptimal conditions, but its effect was smaller than that of the storage environment. These findings emphasize the importance of managing air temperature and relative humidity in storage conditions to preserve seed viability and highlight the potential of seed coating as a supplementary approach in less-controlled storage systems.

Germination speed

Germination speed was influenced by storage environment, while coating effects varied among species. Higher MGT values in shed-stored seeds indicate slower germination than in seeds stored more optimal conditions of indoor climate-controlled or in refrigerated storage. This response corresponds with higher and more variable seed moisture content under these conditions, suggesting that fluctuating storage environments imposed physiological stress that affected germination performance (Hay et al., 2023). These trends are consistent with the reductions in germination observed under shed storage, indicating that factors affecting seed viability also influence speed of germination.

Seed deterioration during storage can disrupt membrane integrity and enzyme systems, requiring repair during early imbibition before metabolic processes proceed toward radicle emergence (Bewley et al., 2013). As a result, seeds stored under unfavorable conditions require

more time to complete germination, while severely deteriorated seeds may fail to germinate (Rajjou & Debeaujon, 2008). In contrast, lower and more stable MGT under refrigerated and indoor storage corresponds with preservation of cellular integrity and metabolic function (Ellis & Roberts, 1980; Harrington, 1972).

Species-specific responses were observed. PR and SCRF showed limited response to coating, whereas TF and KB showed variation in MGT under shed storage. These differences likely reflect variation in seed structure and tolerance to storage-related stress, regardless, more research is needed on this. Days to 50% germination (DG_{50}) followed trends similar to MGT, indicating consistent treatment effects across germination speed metrics (Appendix Tables B.5, B.6, B.7, and B.8). Overall, the storage environment influenced the germination speed, whereas coating effects were smaller and species-dependent.

Seedling vigor

Seedling vigor was also primarily influenced by the storage environment, whereas coating effects were smaller and varied among species. Shed storage reduced shoot and root length relative to indoor and refrigerated conditions, consistent with the higher and more variable seed moisture content observed under these conditions. These responses aligned with declines in germination under shed storage, indicating that storage-induced stress limited both seed viability and subsequent seedling development.

Deterioration during storage can impair membrane integrity and enzyme function, reducing the efficiency of reserve mobilization during germination and early growth (Bewley et al., 2013; Harrington, 1972). In contrast, greater and more stable shoot and root length under refrigerated and indoor conditions highlight the importance of controlled environments in maintaining seed vigor (Ellis & Roberts, 1980). Coating effects on seedling vigor were

inconsistent and species dependent. Coated seed inconsistently produced greater shoot and root length in PR, TF, and SCRF, whereas responses in KB were variable or opposite results. These differences may reflect species-specific coating–seed interactions during germination, including effects on water uptake and early metabolic activation.

The absence of seedling emergence in SCRF under shed storage in Year 2 indicates a complete loss of seed viability after prolonged storage. This suggests that exposure to uncontrolled temperature and humidity accelerates deterioration beyond a critical threshold for this species, resulting in failure of germination rather than a gradual decline in vigor. More research is needed to confirm these species differences and to determine why SCRF may be more adversely affected by suboptimal storage conditions than other cool-season turfgrass species. Ultimately, the storage environment was the primary driver of seedling vigor, with shed storage consistently stunting shoot and root growth across all species. Because seed coatings offered only minimal, inconsistent benefits, maintaining stable storage conditions remains paramount for preserving growth potential.

Pearson correlation analysis further supported the relationships among seed quality traits during long-term storage over two years (Figure 3.4). Germination was positively associated with shoot length, root length, and average seedling dry weight, while negatively associated with MGT and DG_{50} , indicating that seed with greater viability also germinated more rapidly and produced more vigorous seedlings. In contrast, seed moisture content showed only weak correlations with germination and seedling vigor, suggesting that moisture content alone did not explain the observed decline in seed quality across storage environments.

Conclusions

To evaluate seed vigor, researchers often use accelerated seed aging, a stress-simulation technique that uses high temperatures and extreme humidity to artificially speed up deterioration (Park et al., 2022; Zhu et al., 2025). While this is an excellent method for quickly identifying weaker seed lots, it can expose seeds to conditions far harsher than typical storage conditions. Therefore, this experiment focused on simulating real-world storage conditions to gain a more practical understanding of seed viability. This study demonstrated that the long-term storage environment conditions were the primary factors influencing seed moisture content, germination percentage, germination speed, and seedling vigor of cool-season turfgrass seeds. Across both experimental runs, the more optimal storage conditions of refrigeration or a climate-controlled indoor setting maintained relatively stable seed moisture content and preserved germination percentage, germination speed, and seedling vigor more effectively than suboptimal storage conditions of a non-insulated shed environment. The non-insulated shed exposed seed to greater environmental fluctuations, resulting in increased seed moisture variation, reduced germination, slower germination speeds, and lower shoot and root growth, particularly as storage duration increased. Germination remained above 75% under refrigerated and indoor storage across most species and years, except for SCRF, further emphasizing the importance of stable storage environments for maintaining seed viability. Further research is needed on SCRF and similar fine fescue (*Festuca* spp. L) species and subspecies to better understand the potential shorter shelf-life of these taxa compared with other cool-season species.

Coated seed had lower initial seed moisture content than noncoated seed, likely due to the coating and drying process, and this difference was maintained across species, storage conditions, and durations during the study. This suggests that coating may help stabilize seed

moisture content during storage, particularly under variable shed conditions (i.e., suboptimal storage). The coating provided negligible advantages under refrigerated or indoor conditions, where baseline seed quality remained well maintained. The effects of coating on germination percentage, germination speed, and seedling vigor were smaller, inconsistent, and species-dependent. These results indicate that the 1% limestone super-absorbent seed coating used in this study did not uniformly improve these traits across cool-season turfgrass species or storage environments. Therefore, while seed coating may serve as a supplementary tool under suboptimal storage conditions (i.e., non-climate controlled conditions), it cannot replace proper storage practices or fully compensate for poor storage environments.

Overall, maintaining stable storage conditions is critical for preserving cool-season turfgrass seed viability and vigor over time. Refrigerated or indoor, climate-controlled storage should be prioritized for extended storage, whereas non-insulated shed storage should be avoided, especially for species such as TF, KB, and SCRF. These findings provide practical guidance for turfgrass practitioners by highlighting that an appropriate storage environment is more important than relying solely on seed coating technology to maintain seed quality. Future research should evaluate additional coating formulations, a broader range of cool-season turfgrass species and cultivars, and longer storage durations to better understand the interactive effects of seed coating and storage environment on turfgrass seed longevity.

References

- Association of Official Seed Analysts. (1983) Seed Vigor Testing Handbook Contribution No. 32 to The Handbook on Seed Testing. East Lansing, MI. pp.22, 71–74.
- Association of Official Seed Analysts. (2016). *Principles and procedures*. Association of Official Seed Analysts, Inc.
- Avelar, S. A. G., Sousa, F. V. D., Fiss, G., Baudet, L., & Peske, S. T. (2012). The use of film coating on the performance of treated corn seed. *Revista Brasileira de Sementes*, 34, 186–192. <http://doi.org/10.1590/S0101-31222012000200001>
- Beveridge, F. C., Williams, A., & Adkins, S. W. (2020). Seed enhancement technologies to improve germination and emergence of Australian native Poaceae. *Seed Science Research*, 30, 293–303. <https://doi.org/10.1017/S0960258520000276>
- Bewley, J.D., Bradford, K.J., Hilhorst, H.W.M. and Nonogaki, H. (2013) *Seeds: Physiology of Development, Germination and Dormancy*. (3rd ed). Springer, New York. <https://doi.org/10.1007/978-1-4614-4693-4>
- Braun, R. C., Courtney, L. E., & Patton, A. J. (2023). Seed morphology, germination, and seedling vigor characteristics of fine fescue taxa and other cool-season turfgrass species. *Crop Science*, 63, 1613–1627. <https://doi.org/10.1002/csc2.20936>
- Braun, R. C., Mandal, P., Nwachukwu, E., & Stanton, A. (2024). The role of turfgrasses in environmental protection and their benefits to humans: Thirty years later. *Crop Science*, 64, 2909–2944. <https://doi.org/10.1002/csc2.21383>
- Carroll, D. E., Kaminski, J. E., & Landschoot, P. J. (2020). Creeping bentgrass seed germination in growth chambers at optimal and suboptimal temperatures. *Crop, Forage & Turfgrass Management*, 6, e20068. <https://doi.org/10.1002/cft2.20068>
- Christians, N. E., Patton, A. J., & Law, Q. D. (2017). *Fundamentals of turfgrass management* (5th ed). Hoboken, NJ: John Wiley & Sons, Inc.
- Ebdon, J. S., & DaCosta, M. (2020). Soil temperature mediated seedling emergence and field establishment in bentgrass species and cultivars during spring in the Northeastern United States. *HortTechnology*, 31, 42–52. <https://doi.org/10.21273/HORTTECH04653-20>
- El-Maarouf-Bouteau, H., Mazuy, C., Corbineau, F., & Bailly, C. (2011). DNA alteration and programmed cell death during ageing of sunflower seed. *Journal of Experimental Botany*, 62, 5003–5011. <https://doi.org/10.1093/jxb/err198>
- Elias, S. G., Copeland, L. O., McDonald, M. B., & Baalbaki, R. Z. (2012b). Speed of germination and seedling growth rate. *Seed Testing: Principles and Practices*. Michigan State University Press, East Lansing. pp. 155–192.

- Elias, S. G., Copeland, L. O., McDonald, M. B., & Baalbaki, R. Z. (2012a). Seed Moisture Content Testing. *Seed testing: Principles and practices*. Michigan State University Press, East Lansing, MI. pp. 257–270.
- Ellis, R. H., & Roberts, E. H. (1980). Improved equations for the prediction of seed longevity. *Annals of botany*, 45, 13–30.
<https://doi.org/10.1093/oxfordjournals.aob.a085797>
- Fleming, M. B., Hill, L. M., & Walters, C. (2019). The kinetics of ageing in dry-stored seeds: a comparison of viability loss and RNA degradation in unique legacy seed collections. *Annals of Botany*, 123, 1133–1146. <https://doi.org/10.1093/aob/mcy217>
- Goel, A., Goel, A. K., & Sheoran, I. S. (2003). Changes in oxidative stress enzymes during artificial ageing in cotton (*Gossypium hirsutum* L.) seeds. *Journal of Plant Physiology*, 160, 1093–1100. <https://doi.org/10.1078/0176-1617-00881>
- Harman, G.E., & Mattick, L.R. (1976). Association of lipid oxidation with seed ageing and death. *Nature*, 260, 323–324. <https://doi.org/10.1038/260323a0>
- Harrington, J. F. (1972). Seed storage and longevity. In T. T. Kozlowski (Ed.), *Seed Biology* (Vol. 3, pp. 145–245). Academic Press.
- Hay, F. R., Rezaei, S., Wolkis, D., & McGill, C. (2023). Determination and control of seed moisture. *Seed Science and Technology*, 51, 267–285.
<https://doi.org/10.15258/sst.2023.51.2.11>
- Jacob, S. R., Kumar, M. A., Varghese, E., & Sinha, S. N. (2016). Hydrophilic polymer film coat as a micro-container of individual seed facilitates safe storage of tomato seeds. *Scientia Horticulturae*, 204, 116–122. <https://doi.org/10.1016/j.scienta.2016.04.010>
- Jiang, Y., & Su, D. (2018). Models of turfgrass seed germination related to water content. *Plos One*, 13, e0204983. <https://doi.org/10.1371/journal.pone.0204983>
- Kameswara Rao, N., Dulloo, M. E., & Engels, J. M. (2017). A review of factors that influence the production of quality seed for long-term conservation in genebanks. *Genetic Resources and Crop Evolution*, 64, 1061–1074. <https://doi.org/10.1007/s10722-016-0425-9>
- Kranner I (2013). Mechanisms of seed ageing. *South African Journal of Botany*, 86, 140–140.
<https://doi.org/10.1016/j.sajb.2013.02.010>
- Larsen, S. U., & Andreassen, C. (2004). Light and heavy turfgrass seeds differ in germination percentage and mean germination thermal time. *Crop Science*, 44, 1710–1720.
<https://doi.org/10.2135/cropsci2004.1710>
- Larsen, S. U., & Bibby, B. M. (2005). Differences in thermal time requirement for germination of three turfgrass species. *Crop Science*, 45, 2030–2037.
<https://doi.org/10.2135/cropsci2004.0731>

- Larsen, S. U., Andreassen, C., & Kristoffersen, P. (2004). Differential sowing time of turfgrass species affects the establishment of mixtures. *Crop science*, 44, 1315–1322. <https://doi.org/10.2135/cropsci2004.1315>
- Ma, Y. (2019). Seed coating with beneficial microorganisms for precision agriculture. *Biotechnology Advances*, 37, 107423. <https://doi.org/10.1016/j.biotechadv.2019.107423>
- Maleki Farahani, S., Rezazadeh, A., & Paravar, A. (2025). Influence of seed moisture content and storage period on germination and biochemical indices: *Lallemantia iberica* and *Lallemantia royleana*. *Scientific Reports*, 15, 4462. <https://doi.org/10.1038/s41598-025-88881-w>
- Mao, P. S., Wang, X. G., Wang, Y. H., & Han, J. G. (2009). Effect of storage temperature and duration on the vigor of zoysiagrass (*Zoysia japonica* Steud.) seed harvested at different maturity stages. *Grassland Science*, 55, 1–5. <https://doi.org/10.1111/j.1744-697X.2009.00129.x>
- Munshaw, G. C., Layton, J. M., Stewart, B. R., Philley, H. W., Beasley, J. S., & Lemus, R. W. (2014). The Germination responses of five bermudagrass cultivars to seed coating and temperature. *HortScience*, 49, 1225–1229. <https://www.doi.org/10.21273/HORTSCI.49.9.1225>
- Park, K., Lee, S. Y., Ji, B., Jang, B. K., Lee, H., Lee, H., ... & Cho, J. S. (2022). Seed longevity and germinability of *Pulsatilla dahurica* (Fisch. ex DC.) spreng after storage and accelerated aging test. *Horticultural Science and Technology*, 40, 147–156. <https://doi.org/10.7235/HORT.20220014>
- Pedrini, S., Balestrazzi, A., Madsen, M. D., Bhalsing, K., Hardegree, S. P., Dixon, K. W., & Kildisheva, O. A. (2020). Seed enhancement: getting seeds restoration-ready. *Restoration Ecology*, 28, S266–S275. <https://doi.org/10.1111/rec.13184>
- Pedrini, S., Merritt, D. J., Stevens, J., & Dixon, K. (2017). Seed coating: Science or marketing spin?. *Trends in Plant Science*, 22, 106–116. <https://doi.org/10.1016/j.tplants.2016.11.002>
- Probert, R. J., Daws, M. I., & Hay, F. R. (2009). Ecological correlates of ex situ seed longevity: a comparative study on 195 species. *Annals of botany*, 104, 57–69. <https://doi.org/10.1093/aob/mcp082>
- Rajjou, L., & Debeaujon, I. (2008). Seed longevity: survival and maintenance of high germination ability of dry seeds. *Comptes rendus biologiques*, 331, 796–805. <https://doi.org/10.1016/j.crvi.2008.07.021>
- Reed, R. C., Bradford, K. J., & Khanday, I. (2022). Seed germination and vigor: ensuring crop sustainability in a changing climate. *Heredity*, 128, 450–459. <https://doi.org/10.1038/s41437-022-00497-2>

- Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, 52, 591–611. <https://doi.org/10.1093/biomet/52.3-4.591>
- Sohail, M., Pirzada, T., Opperman, C. H., & Khan, S. A. (2022). Recent advances in seed coating technologies: transitioning toward sustainable agriculture. *Green Chemistry*, 24, 6052–6085. <https://doi.org/10.1039/D2GC02389J>
- Stier, J. C., Steinke, K., Ervin, E. H., Higginson, F. R., & McMaugh, P. E. (2013). Turfgrass benefits and issues. *Turfgrass: Biology, use, and management*, 56, 105–145. <https://doi.org/10.2134/agronmonogr56.c3> Digital Object Identifier (DOI)
- Taylor, A. G., Allen, P. S., Bennett, M. A., Bradford, K. J., Burris, J. S., & Misra, M. K. (1998). Seed enhancements. *Seed Science Research*, 8, 245–256. <https://doi.org/10.1017/S0960258500004141>
- Taylor, A. G., Grabe, D. F., & Paine, D. H. (1997). Moisture content and water activity determination of pelleted and film-coated seeds. *Seed Technology*, 24–32. <https://www.jstor.org/stable/23433247>
- Teveni III, P. C., Cox, R. D., & Cooper-Norris, C. E. (2024). Temperature Effects on Huisache (*Vachellia farnesiana* (L.) Wight & Arn.) Seed Germination. *Rangeland Ecology & Management*, 96, 197–202. <https://doi.org/10.1016/j.rama.2024.07.004>
- Walters, C., Ballesteros, D., & Vertucci, V. A. (2010). Structural mechanics of seed deterioration: standing the test of time. *Plant Science*, 179, 565–573. <https://doi.org/10.1016/j.plantsci.2010.06.016>
- Walters, C., Wheeler, L. M., & Grotenhuis, J. M. (2005). Longevity of seeds stored in a genebank: species characteristics. *Seed Science Research*, 15, 1–20.
- Welty, R. E., Azevedo, M. D., & Cooper, T. M. (1987). Influence of moisture content, temperature, and length of storage on seed germination and survival of endophytic fungi in seeds of tall fescue and perennial ryegrass. *Phytopathology*, 77, 893–900. <https://doi.org/10.1094/Phyto-77-893>
- Zhu, H., Yang, R., Lu, M., Shi, W., Sun, W., Lv, D., ... & Han, Z. (2025). Identification of maize seed vigor under different accelerated aging times using hyperspectral imaging and spectral deep features. *Computers and Electronics in Agriculture*, 231, 109980. <https://doi.org/10.1016/j.compag.2025.109980>
- Zinsmeister, J., Leprince, O., & Buitink, J. (2020). Molecular and environmental factors regulating seed longevity. *Biochemical Journal*, 477, 305–323. <https://doi.org/10.1042/BCJ20190165>

Chapter 4 - Effects of Seed Coating, Irrigation Regimes, and Soil Texture on Turfgrass Establishment in Controlled Environment

Abstract

The coating of turfgrass seed is often marketed to improve germination, early growth, and potentially reduce water inputs; however, its effectiveness for turfgrass establishment is poorly understood. Three greenhouse experiments were conducted during 2023 through 2025 to quantify the effects of seed coating, irrigation regimes, and soil types on the establishment of turfgrass species: perennial ryegrass (*Lolium perenne* L.), tall fescue (*Festuca arundinacea* Schreb.), strong creeping red fescue (*Festuca rubra* L. ssp. *rubra* Gaudin), Kentucky bluegrass (*Poa pratensis* L.), and bermudagrass [*Cynodon dactylon* (L.) Pers.]. Experiment 1 explored two coating types (noncoated vs. coated) and two irrigation amounts (2.5 vs. 5.1 mm d⁻¹). Experiment 2 investigated coating type, irrigation frequency (daily vs. every 2 d), and soil types (sand vs. silt loam). Experiment 3 examined coating type, irrigation frequency (daily vs. every 3 d), and soil types. Across all three experiments, these treatment factors were investigated within the multiple turfgrass species. Measurements included seedling emergence, turf cover, and population counts. Across experiments, seed coating had a minimal effect on seedling emergence or early establishment across all five species. As expected, higher irrigation amounts or more frequent irrigation applications enhanced early turf cover development only within the first 40 days after planting. Soil type was the most consistent factor influencing turfgrass establishment, with silt loam soil producing greater turfgrass cover than sandy soil. Overall, adequate irrigation practices and moisture-retentive soils were more critical for successful turfgrass establishment and seed coating was generally ineffective.

Introduction

Turfgrass systems provide a range of ecosystem services, including improved soil health, enhanced water quality, reduced stormwater runoff, evaporative cooling to mitigate urban heat, and support for biodiversity, in addition to contributing to human well-being (Braun et al., 2024). Despite these benefits, turfgrass often requires supplemental irrigation, especially during establishment when adequate soil moisture is essential for successful seedling emergence and sward development (Barton & Colmer, 2006). Efficient irrigation during establishment is crucial for uniform growth and for turfgrass systems to provide long-term ecosystem services. Adequate soil moisture supports seed germination and early seedling vigor, while water shortages can delay emergence, weaken seedlings, and increase the risk of desiccation and mortality (Braun et al., 2022b; Huang, 2008).

Turfgrasses are classified as warm- or cool-season species, each with distinct water-use characteristics (Braun et al., 2022a, 2022b; Colmer & Barton, 2017). Warm-season species such as bermudagrass [*Cynodon dactylon* (L.) Pers.] or buffalograss [*Bouteloua dactyloides* (Nutt.) J.T. Columbus] are generally more efficient water users, whereas cool-season species require more frequent irrigation due to their C₃ pathway and often have shallower rooting depths (Fry & Huang, 2004). However, water-use demands vary among species and cultivars and are strongly influenced by environmental conditions as well (Braun et al., 2022a, 2022b).

Turfgrass expansion in urban landscapes has increased irrigation demands, further stressing limited water supplies in arid and semi-arid regions (Wynne & Devitt, 2020). To address the issue, industries are moving towards seed-coating technology, which may assist in establishing turfgrass systems with reduced water inputs. It is widely used in agricultural and horticultural systems; however, it remains an emerging concept in the turfgrass industry with

very little research to support claims. Seed coating is the application of external materials to seeds, to improve germination, vigor, establishment, water-use efficiency, and stress tolerance (Rocha et al., 2019). Various materials are used in seed coatings including nutrients, growth regulators, surfactants, polymers, binders, fillers, and pesticides to modify the seed microenvironment (Paravar et al., 2023). While seed coating technologies have been extensively studied in agronomic crops, their application in turfgrass systems remains relatively limited (see Chapter 1). Consequently, there is a need to better understand how seed coatings may influence turfgrass establishment under water-limited and other abiotic stress conditions.

In turfgrass systems, polymer-based coatings such as ZEBA have improved establishment under limited irrigation and low seeding density in bermudagrass, creeping bentgrass (*Agrostis stolonifera* L.), and cool-season turfgrass mixtures (Leinauer et al., 2010). Surfactant-based coatings have also demonstrated potential, particularly in hydrophobic soils, by enhancing soil water content, germination, and early growth of tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] (TF) and perennial ryegrass (*Lolium perenne* L.) (PR) (Madsen et al., 2013, 2014, 2016, 2017). Furthermore, McMillan et al. (2023) reported that surfactant-coated perennial ryegrass achieved comparable or superior turfgrass establishment to noncoated seed, even with half the seeding rate compared with the noncoated seed. Earlier greenhouse studies reported neutral or positive effects of adhesive-based limestone coatings and fertilizer coatings on Kentucky bluegrass (*Poa pratensis* L.) (KB) and tall fescue establishment (Hathcock et al., 1984a, 1984b). Conversely, polymer-coated seed delayed early establishment in several cool- and warm-season species, though coating had no effect on days to reach 95% coverage. (Serena et al., 2012a, 2012b). Additional studies have shown limited or no effects of seed coatings on germination or establishment of tall

fescue, Kentucky bluegrass, and multiple bermudagrass cultivars (Richardson & Hignight, 2010; Munshaw et al., 2014; Layton et al., 2007). Collectively, these findings highlight mixed responses to seed-coating technology in turfgrass systems. These inconsistencies may be attributed to the use of a limited range of turfgrass species and coating materials, as well as to companies' lack of transparency regarding seed-coating composition due to proprietary restrictions. At this time, less than 20 peer-reviewed publications in the last 30 years have examined seed coating in turfgrass systems, creating a gap between public and private research (see Chapter 1 for a comprehensive review). Given the increasing pressure for continued water conservation, further research is needed to determine whether seed coatings can improve establishment efficiency under varying irrigation and soil conditions. To address this need, the objectives of this paper were to measure seedling emergence and turfgrass establishment characteristics within multiple turfgrass species influenced by seed coatings (Experiments 1, 2, & 3), irrigation amounts (Experiment 1), irrigation frequencies (Experiment 2 & 3), and soil types (Experiment 2 & 3).

Materials and Methods

Experiment design and management

Three greenhouse experiments (Experiments 1, 2, and 3) were conducted at the Throckmorton Plant Sciences Center, Kansas State University, Manhattan, KS (39° 11' 50" N, 96° 35' 27" W) (Appendix Figure C.1). Experiments 1 and 2 were conducted from 26 June to 15 August 2023 and repeated from 28 May to 17 July 2024 (50-day duration) (Table 4.1). Experiment 3 was conducted from 15 May to 29 June 2025 and repeated from 24 June to 8 August 2025 (45-day duration) (Table 4.1). Four cool-season turfgrass species were included in

Experiments 1 and 2: perennial ryegrass, tall fescue, strong creeping red fescue (*Festuca rubra* L. ssp. *rubra* Gaudin) (SCRf), and Kentucky bluegrass (Table 4.1). Noncoated and coated seeds (coating with 1% limestone super-absorbent) were evaluated for each species. Experiment 3 included bermudagrass noncoated and coated seeds with 50% coating material consisting of lime, STEP UP (nutrient-based seed treatment additive), and Apron XL (fungicide). Seeds for all experiments were supplied by Mountain View Seeds Company (Oregon, USA). The greenhouse photoperiod was ~15 hours for all experiments. Day/night temperatures were maintained at 23/18 °C for Experiments 1 and 2, and warmer temperatures of 32/21 °C for Experiment 3 because it investigated a warm-season species. An environmental sensor (HOBO USB Micro Station Data Logger with Photosynthetic Light (PAR) Smart Sensor, H21-USB, HOBO Data Loggers, Bourne, MA, USA) monitored temperature, relative humidity, and photosynthetically active radiation in the greenhouse.

Experiment 1 evaluated four cool-season turfgrass species using a two-way factorial (seed coating $\times$ irrigation amount) arrangement in a randomized complete-block design with four replications (blocks) and repeated over time. Treatments included two seed coating types (noncoated vs. coated) and two irrigation amounts (2.5 vs. 5.1 mm d⁻¹) using a loam soil (51% sand, 35% silt, and 14% clay) (Table 4.1). Experiment 2 evaluated the same four cool-season turfgrass species as Experiment 1 using a three-way factorial (seed coating $\times$ irrigation frequency $\times$ soil type) arrangement in a randomized complete-block design with four replications (blocks) and repeated over time. Treatments included two seed coating types (noncoated vs. coated); two irrigation frequencies (5.1 mm d⁻¹ vs. 5.1 mm every 2 d), and two soil types (silt loam vs. sand) (Table 4.1). More specifically, silt loam consisted of (30% sand, 52% silt, and 18% clay), and sand soil consisted of (97% sand and 3% clay). Experiment 3 evaluated seeded bermudagrass

using a three-way factorial arrangement in a randomized complete-block design with four replications (blocks) and repeated over time. Treatments included two seed coating types (noncoated vs. coated); two irrigation frequencies (5.1 mm d⁻¹ vs. 5.1 mm every 3 d), and two soil types (silt loam vs. sand) (Table 4.1). The silt loam and sand soil were the same as in Experiment 2. All three experiments used 10.6 × 10.6 cm greenhouse pots (4.2 × 4.2 inch).

Table 4.1. Details of species investigated and treatment factors in Experiments 1, 2, and 3.

Experiment	Species ^a	Coating	Irrigation Amount	Irrigation Frequency	Soil Type
1	'Fastball 3 GL' perennial ryegrass, 'Dynamite GLS' tall fescue, 'Cardinal 2' strong creeping red fescue, 'Selway' Kentucky bluegrass	Noncoated vs. coated	2.5 mm d ⁻¹ vs. 5.1 mm d ⁻¹	-- ^b	-- ^b
2	'Fastball 3 GL' perennial ryegrass, 'Dynamite GLS' tall fescue, 'Cardinal 2' strong creeping red fescue, 'Selway' Kentucky bluegrass	Noncoated vs. coated	--	5.1 mm d ⁻¹ vs. 5.1 mm every 2 d	Silt loam vs. sand
3	'Rio' bermudagrass	Noncoated vs. coated	--	5.1 mm d ⁻¹ vs. 5.1 mm every 3 d	Silt loam vs. sand

^a Species was not a treatment factor in any experiment, but treatment factors were analyzed within each species investigated.

^b Soil type was the same for all treatments in Experiment 1, which was a loam soil (56% sand, 31% silt, and 14% clay) and irrigation frequency occurred every day.

Seeding

A starter fertilizer (20-27-5, Menards Starter Fertilizer, Eau Claire Coop Oil Co.) was applied at a rate of 161 kg ha⁻¹ (44 kg N ha⁻¹ and 32 kg P₂O₅ ha⁻¹) by hand for all experiments. Seed was applied by hand and lightly incorporated into the top 5 mm of soil (Appendix Figure C.2). To ensure uniform and consistent seeding across all treatments, the pure live seeding rate for each pot was calculated using standard laboratory procedures (Association of Official Seed

Analysts [AOSA], 2016; USDA NRCS, 2011). The seed purity rate (from seed labels) of each turfgrass species, and all seed germination tests were conducted within 3 months of each experiment to determine pure live seed for each species. Thousand seed-weight counts were conducted for each turfgrass species and coating type. These counts were combined with pure live seed to calculate seed weights per pot, corresponding to the equivalent 2 pure live seed cm^{-2} for each species included across all three experiments (Table 4.2). This method ensured that each pot received the same number of seeds, regardless of whether the seeds were coated or noncoated, which varied in weight (Table 4.2).

Table 4.2. Pure live seed (PLS) rates and seed weights used per pot for turfgrass species in Experiments 1, 2 and 3.

	Species	Cultivar	Coating	Seeding rate PLS cm^{-2}	Seed weight (g pot^{-1})
Experiments 1 and 2	Perennial ryegrass	Fastball 3 GL	Noncoated	2	0.43
			Coated	2	0.90
	Tall fescue	Dynamite GLS	Noncoated	2	0.59
			Coated	2	1.33
	Strong creeping red fescue	Cardinal 2	Noncoated	2	0.35
			Coated	2	0.74
	Kentucky bluegrass	Selway	Noncoated	2	0.07
			Coated	2	0.15
Experiment 3	Bermudagrass	Rio	Noncoated	2	1.07
			Coated	2	2.49

Irrigation

All pots were irrigated immediately after seeding to wet the entire soil profile, and then irrigation treatments began the following day. In Experiment 1, two irrigation amounts were implemented at 2.5 mm d^{-1} or 5.1 mm d^{-1} (equivalent to 28.8 and 58 mL pot^{-1} , respectively). In Experiment 2, two irrigation frequencies were executed at 5.1 mm d^{-1} or 5.1 mm every 2 d. In Experiment 3, two irrigation frequencies were performed at 5.1 mm d^{-1} or 5.1 mm every 3 d.

Irrigation treatments were applied manually with a graduated cylinder for 28 days in all experiments.

Data collection

Seedling emergence was noted when the tip of the leaf first appeared above the soil surface (Braun et al., 2021). Pots were monitored daily until all pots had successful seedling emergence, and the average number of days to first seedling emergence was calculated. Visual turfgrass cover (0 to 100%) was assessed every 5 d from 5 to 50 d after planting (DAP) in Experiments 1 and 2, and up to 45 DAP in Experiment 3 (Appendix Figure C.3). Percent green cover (0 to 100%) was measured using digital image analysis (Richardson et al., 2001) every 5 d from 5 to 45 or 50 DAP in all Experiments (Appendix Figure C.4). Images were taken with a Nikon Z30 digital camera (Nikon Inc., Japan) mounted on a customized 25-cm diameter lightbox container with 28 cm depth. Manual camera settings were f/4.5, ISO 125, 1/80 s shutter speed, and images were 3712 × 5668 pixels and 300 dpi. Images were analyzed using Turf Analyzer 1.0.4 (Green Research Services, LLC, Fayetteville, AR) with threshold settings hue: 70-170, saturation: 5-100%, and brightness: 0-100% and a frame threshold settings of hue: 171-255, saturation: 25-100%, brightness: 0-100% to calculate green pixels relative to non-green area (e.g., soil, pot, black cloth). Visual grid counts for turf cover percentage were collected at 15, 25, 35, and 45 DAP using a modification of the vertical point quadrat method (Braun et al., 2021; Gaussoin & Branham, 1989), where a 10.2 × 10.2 cm frame was set above the pot with a filament grid of 81 intersections (Appendix Figure C.5). The total number of instances of turfgrass present under each intersection was recorded for each pot, and the percentage of turfgrass cover was then calculated.

Data analysis

Analysis of variance for seedling emergence, visual turf cover, percent green cover, and grid counts was conducted in SAS version 9.4 (SAS Institute Inc.) utilizing the GLIMMIX procedure to determine the main effects and interactions at a 0.05 significance level within each turfgrass species. Data from the two runs of each experiment were pooled for analysis because the run $\times$ treatment interactions were not significant. The Shapiro-Wilk test (Shapiro & Wilk, 1965) was used to assess the normality of residuals. Means were separated using Fisher's protected LSD test ($\alpha = 0.05$) when F -tests were significant ($P \leq 0.05$) within each species.

Results

Seedling emergence

In Experiment 1, seedling emergence (first day of seedling emergence) was not influenced by seed coating, irrigation amounts, or their interaction within any species (Appendix Table C.1), except KB, where noncoated seeds emerged 0.5 d earlier than coated seeds. Overall, no meaningful differences were observed in seedling emergence speed.

In Experiment 2, an irrigation frequency $\times$ soil type interaction occurred only in KB, where the irrigation applied every 2 days $\times$ silt loam and daily irrigation $\times$ silt loam provided seedling emergence of 0.3 to 0.8 d earlier compared with treatments containing sandy soil (Appendix Tables C.2 and C.3). Among the main effects, both seed coating and irrigation frequency did not influence seedling emergence for any species. The silt loam soil type provided seeded emergence of 0.2 to 0.6 d earlier in TF, SCRF, and KB compared with sand soil (Appendix Table C.2). Again, no notable differences occurred with seedling emergence speeds.

In Experiment 3, irrigation frequency and soil type influenced the bermudagrass emergence (Appendix Table C.4). An irrigation frequency $\times$ soil type interaction was observed in bermudagrass, where seedling emergence occurred in 7.0 and 9.3 d under daily irrigation in silt loam and sand, respectively, whereas irrigation every 3 d delayed seedling emergence to 12.6 d in silt loam and 45.1 d in sand (Appendix Table C.5). Across main effects, seedling emergence occurred 20.7 d earlier under daily irrigation than under irrigation applied every 3 d and 17.4 d earlier in silt loam soil compared with sand soil. Overall, seedling emergence across all three experiments was more influenced by irrigation regimes and soil types than by seed coating.

Turf cover

Visual turf cover

In Experiment 1, a seed coating $\times$ irrigation amount interaction was not observed for any species, except for SCRF at 50 DAP, where coated seed under the higher irrigation amount (5.1 mm d⁻¹) produced 67% turf cover, while noncoated seed under the lower irrigation amount (2.5 mm d⁻¹) produced similar turf cover (64%) (Table 4.3; Appendix Table C.7). Across species, irrigation treatment was the most consistent factor influencing visual turf cover (Table 4.3). The higher irrigation amount (5.1 mm d⁻¹) accelerated early canopy development (20–30 DAP) in PR, TF, and SCRF, though differences diminished as turfgrass reached 40–50 DAP. Kentucky bluegrass did not respond to irrigation amount (Figure. 4.1; Appendix Table C.6). Seed coating effects were observed only in TF, where coated seed had 18.8% turf cover compared with noncoated seed at 14.6% at 10 DAP; however, both treatments were between 70 to 80% turf cover by 50 DAP, indicating that coating benefits were confined to early establishment (Appendix Table C.6). Overall, irrigation treatment was the dominant factor influencing early turf cover, whereas coating effects were inconsistent and species-specific.

In Experiment 2, no three- or two-way interactions were observed among seed coating, irrigation frequency, and soil type (Appendix Tables C.8 and C.9), except a coating $\times$ soil type interaction occurred in SCRF at 10 DAP, where noncoated seed in silt loam produced greater turf cover (17.5%) than coated seed in silt loam (13.8%). However, both silt loam treatments outperformed sand soil treatments (Appendix Table C.10). Soil type was the most consistent factor influencing turf cover, with silt loam producing greater turf cover than sand across all species (Table 4.3; Appendix Tables C.8 and C.9). The magnitude of soil effect ranged from 7 to 48% depending on species and time (Figure. 4.2). Coating responses were inconsistent: PR showed a small early advantage of coated seed (21.6% vs. 18.3%) at 10 DAP, whereas the opposite response occurred in SCRF (14.4% vs. 12.6%) at the same time point (Table 4.3). These effects were limited to one data point, and no coating effects were observed in TF or KB. Overall, soil type exerted a stronger and more consistent influence on turf cover than either coating or irrigation frequency.

In Experiment 3, the irrigation frequency $\times$ soil type interaction influenced bermudagrass cover (Table 4.4). Under daily irrigation, visual turf cover was consistently greater in silt loam than sand, increasing from 6% (silt loam) vs. 2% (sand) at 15 DAP to 59% (silt loam) vs. 14% (sand) at 45 DAP (Figure. 4.3). In contrast, turf cover remained $<3\%$ in both soils when irrigation was applied every 3 d, indicating that reduced irrigation frequency limited establishment regardless of soil type. Among main effects, noncoated seed produced 1 to 6.6% greater turf cover than coated seed from 15 to 45 DAP (Appendix Table C.11). Daily irrigation resulted in 36% turf cover at 45 DAP compared with only 4% turf cover under irrigation every 3 d. Similarly, silt loam produced 34% turf cover compared with 7% in sand at 45 DAP (Appendix

Table C.11). Overall, successful establishment of seeded bermudagrass depends on irrigation frequency and soil type, with limited influence from seed coating.

Percent green cover

In Experiment 1, no seed coating $\times$ irrigation amount interaction occurred in any species (Table 4.5). Seed coating increased the percent green cover by 13 to 32% in PR and 23 to 37% in TF during early establishment (10–20 DAP). However, this advantage declined to 8% by 40 DAP, and no coating effects were observed in SCRF or KB (Table 4.5; Appendix Table C.12), indicating that coating effects were limited to early establishment and were species dependent. Irrigation amount had a greater influence on percent green cover across species except KB (Table 4.5; Appendix Table C.12). The higher irrigation amount (5.1 mm d⁻¹) increased the percent green cover by approximately 43 to 54% in PR, TF, and SCRF during early establishment (20–30 DAP). However, at a later establishment stage (50 DAP), the lower irrigation amount (2.5 mm d⁻¹) produced greater green cover in PR (33% increased green cover) and TF (14% increased green cover), with no effects observed in SCRF and KB (Appendix Table C.12).

Table 4.3. Analysis of variance (ANOVA) p values for visual turf cover at 10, 20, 30, 40 and 50 DAP in multiple cool-season turfgrasses in Experiment 1 (Seed coating $\times$ Irrigation amount) and Experiment 2 (Seed coating $\times$ Irrigation frequency $\times$ Soil type).

Visual turf cover												
Species	Factors	EXPERIMENT 1					EXPERIMENT 2					
		10	20	30	40	50	Factors	10	20	30	40	50
		DAP	DAP	DAP	DAP	DAP		DAP	DAP	DAP	DAP	DAP
<i>p values</i>												
Perennial ryegrass	Coating	0.1883	0.6633	0.3798	0.0622	0.2496	Coating	0.0085	0.4641	0.3043	0.1424	0.0687
	Irrigation amount	0.1432	0.0001	0.0001	0.7826	0.0101	Irrigation frequency	0.7247	0.1642	0.1767	0.9619	0.6319
	Coating × Irrigation amount	0.1645	0.7885	0.4211	0.3733	0.9628	Soil type	0.2301	0.0052	<.0001	<.0001	<.0001
Tall fescue	Coating	0.0083	0.1074	0.0606	0.0040	0.0179	Coating	0.2138	1.0000	0.8220	0.7793	0.4175
	Irrigation amount	0.6068	0.0005	0.0021	0.2102	0.5711	Irrigation frequency	0.655	0.0728	0.1044	0.242	0.1549
	Coating × Irrigation amount	0.6068	0.5382	0.8850	0.6957	0.7765	Soil type	0.0009	0.1297	0.0022	<.0001	<.0001
Strong creeping red fescue	Coating	0.2576	0.2489	0.6223	0.1021	0.2730	Coating	0.0126	0.9874	0.8433	0.8367	0.3473
	Irrigation amount	0.1768	0.0016	0.0034	0.0126	0.4482	Irrigation frequency	0.6201	0.0564	0.0795	0.1348	0.3324
	Coating × Irrigation amount	0.3071	0.9325	0.9157	0.2405	0.0215	Soil type	<.0001	0.0457	0.0188	<.0001	<.0001
Kentucky bluegrass	Coating	0.8808	0.2744	0.5515	0.7485	0.7231	Coating	0.1955	0.0908	0.1031	0.2877	0.1081
	Irrigation amount	0.1081	0.3743	0.1551	0.4961	0.7948	Irrigation frequency	0.7942	0.2956	0.1981	0.3326	0.6249
	Coating × Irrigation amount	0.4558	0.6740	0.9320	0.5685	0.7767	Soil type	0.0005	0.0270	0.0362	0.0107	0.0022

Note: Bolded p values indicate significance at $p < 0.05$; Abbreviation: DAP = days after planting

Table 4.4. Analysis of variance (ANOVA) *p* values for visual turf cover at 15, 25, 35 and 45 days after planting in bermudagrass (warm-season turfgrass) in Experiment 3 (Seed coating $\times$ Irrigation frequency $\times$ Soil type).

Species	Factors	Visual turf cover EXPERIMENT 3			
		<i>p</i> values			
		15 DAP	25 DAP	35 DAP	45 DAP
Bermudagrass	Coating	0.0169	0.0512	0.0161	0.0109
	Irrigation frequency	<.0001	<.0001	<.0001	<.0001
	Coating $\times$ Irrigation frequency	0.0917	0.2607	0.1645	0.1285
	Soil type	<.0001	<.0001	<.0001	<.0001
	Coating $\times$ Soil type	0.1195	0.3605	0.1404	0.1844
	Irrigation frequency $\times$ Soil type	0.0014	<.0001	<.0001	<.0001
	Coating $\times$ Irrigation frequency $\times$ Soil type	0.4088	0.9489	0.6751	0.8043

Note: Bolded *p* values indicate significance at $p < 0.05$; Abbreviation: DAP = days after planting

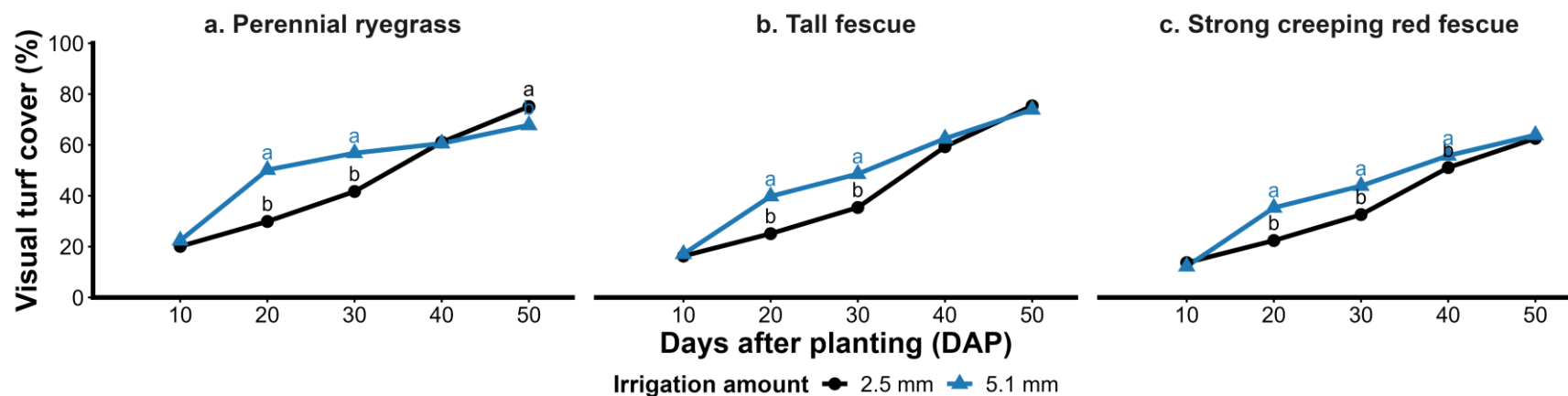


Figure 4.1. Effect of irrigation amount on visual turf cover (%) of perennial ryegrass, tall fescue, and strong creeping red fescue in Experiment 1 across days after planting (DAP). *Note:* Letters within each DAP within each species indicate significant differences according to Fisher's protected LSD test ($\alpha = 0.05$).

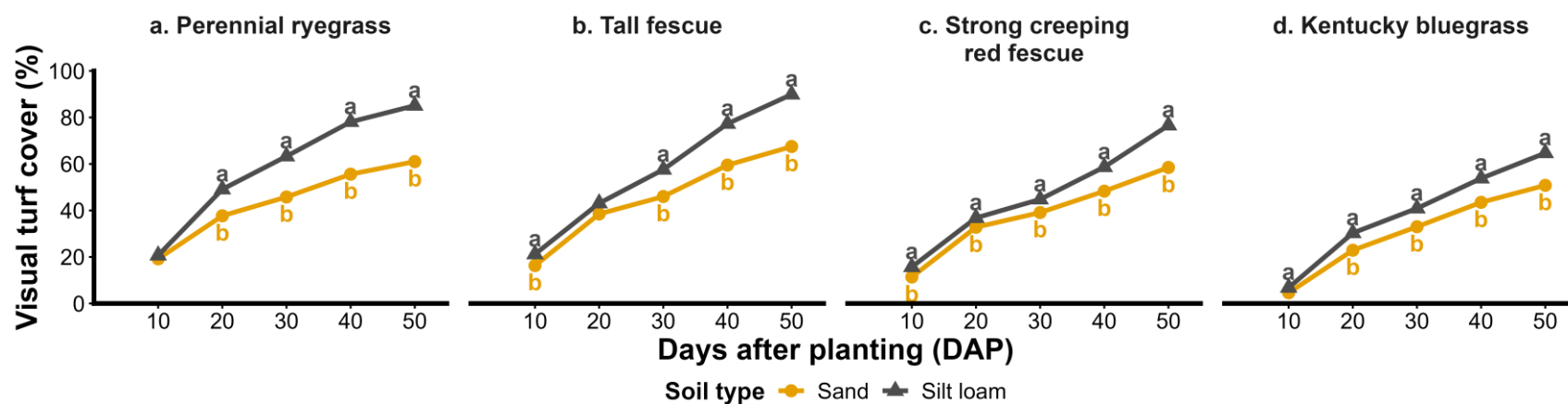


Figure 4.2. Effect of soil type on visual turf cover (%) of perennial ryegrass, tall fescue, strong creeping red fescue, and Kentucky bluegrass in Experiment 2 across days after planting (DAP). *Note:* Letters within each DAP within each species indicate significant differences according to Fisher's protected LSD test ($\alpha = 0.05$).

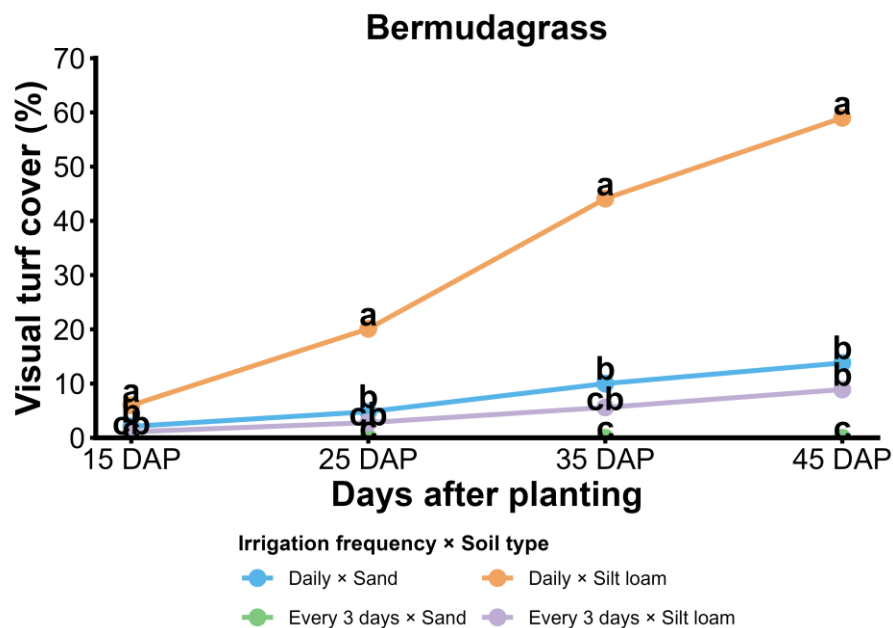


Figure 4.3. Effect of the irrigation frequency $\times$ soil type interaction on visual turf cover (%) of bermudagrass across days after planting (DAP) in Experiment 3. *Note:* Letters within each DAP indicate significant differences according to Fisher's protected LSD test ($\alpha = 0.05$).

In Experiment 2, only a few interactions were observed, and these were limited to only one time point. For these significant interactions, a similar trend as visual turf cover was observed, which included the more frequent irrigation treatment and the silt loam soil resulted in more green cover in TF and SCRF at times (Appendix Tables C.13 and C.14, and Appendix Figure. C.1). No two- or three-way interactions occurred in PR or KB. Among main effects, soil type was the most consistent factor influencing percent green cover across species (Table 4.5), where silt loam produced, on average, 41 to 73% greater green cover than sand (Appendix Tables C.13 and C.14). Similar to Experiment 1, seed coating effects were minor, inconsistent, and often limited to early establishment within the first 30 DAP, where coated seed increased green cover by <20% in PR (10–20 DAP) and in KB (30 DAP) (Table 4.5). Irrigation frequency influenced green cover during early development (20–30 DAP), with daily irrigation resulting in

20 to 35% greater green cover compared with irrigation every 2 d; however, no differences were observed ≥ 40 DAP.

In Experiment 3, only the irrigation frequency $\times$ soil type interaction influenced percent green cover (Table 4.6). Daily irrigation in silt loam consistently produced greater green cover across all dates, ranging from 9 to 56%, compared with 2 to 12% in sand (Table 4.6). In contrast, the 3-day irrigation interval resulted in $<10\%$ green cover in both soils (Appendix Table C.16). Overall, coated bermudagrass seed did not positively enhance establishment measured by both visual turf cover and percent green cover in this experiment (Appendix Table C.15).

Table 4.5. Analysis of variance (ANOVA) p values for percent green cover at 10, 20, 30, 40 and 50 days after planting in perennial ryegrass, tall fescue, strong creeping red fescue and Kentucky bluegrass in Experiment 1 and Experiment 2.

Species	EXPERIMENT 1						EXPERIMENT 2					
	Factors	10	20	30	40	50	Factors	10	20	30	40	50
		DAP	DAP	DAP	DAP	DAP		DAP	DAP	DAP	DAP	DAP
<i>p values</i>												
Perennial ryegrass	Coating	0.0112	0.0044	0.13	0.0418	0.4287	Coating	0.0999	0.0255	0.054	0.5236	0.9084
	Irrigation amount	0.011	<.0001	<.0001	0.5279	<.0001	Irrigation frequency	0.5625	<.0001	0.0001	0.9688	0.355
	Coating × Irrigation amount	0.8288	0.4545	0.1709	0.3198	0.7219	Soil type	<.0001	0.0053	<.0001	<.0001	<.0001
Tall fescue	Coating	0.0379	0.0006	0.008	0.036	0.1674	Coating	0.901	0.3013	0.947	0.7652	0.5589
	Irrigation amount	0.6935	<.0001	<.0001	0.0069	0.0017	Irrigation frequency	0.3762	<.0001	<.0001	0.1765	0.763
	Coating × Irrigation amount	0.5739	0.519	0.8854	0.7169	0.5456	Soil type	<.0001	0.0025	<.0001	<.0001	<.0001
Strong creeping red fescue	Coating	0.5737	0.0569	0.2171	0.1352	0.5342	Coating	0.3209	0.9383	0.5101	0.4346	0.8867
	Irrigation amount	0.9927	<.0001	<.0001	0.0231	0.2964	Irrigation frequency	0.3472	<.0001	<.0001	0.4313	0.8715
	Coating × Irrigation amount	0.4242	0.7208	0.6804	0.8564	0.6286	Soil type	<.0001	<.0001	<.0001	<.0001	<.0001
Kentucky bluegrass	Coating	0.6775	0.2686	0.1443	0.3923	0.5538	Coating	0.7939	0.0671	0.0028	0.1324	0.2825
	Irrigation amount	0.5394	0.1112	0.0035	0.6347	0.1712	Irrigation frequency	0.0039	0.0299	0.0020	0.2272	0.7869
	Coating × Irrigation amount	0.3563	0.392	0.8219	0.1553	0.2023	Soil type	0.6729	<.0001	<.0001	<.0001	<.0001

Note: Bolded p values indicate significance at $p < 0.05$; Abbreviation: DAP = days after planting

Table 4.6. Analysis of variance (ANOVA) *p* values for percent green cover at 15, 25, 35 and 45 days after planting in bermudagrass in Experiment 3.

Species	Factors	EXPERIMENT 3			
		<i>p</i> values			
		15 DAP	25 DAP	35 DAP	45 DAP
Bermudagrass	Coating	0.0654	0.0725	0.248	0.7065
	Irrigation frequency	<.0001	<.0001	<.0001	<.0001
	Coating × Irrigation frequency	0.2751	0.1716	0.3209	0.7607
	Soil type	<.0001	<.0001	<.0001	<.0001
	Coating × Soil type	0.2128	0.4269	0.875	0.9047
	Irrigation frequency × Soil type	0.0017	<.0001	<.0001	0.04
	Coating × Irrigation frequency × Soil type	0.6322	0.7246	0.9932	0.8486

Note: Bolded *p* values indicate significance at $p < 0.05$; Abbreviation: DAP = days after planting

Grid count

In Experiment 1, no seed coating $\times$ irrigation amount interactions were observed for any species, except for SCRF at 45 DAP ($P = 0.0128$), where coated seed under 5.1 mm irrigation (82.9%) produced greater turf cover than coated seed under 2.5 mm irrigation (72.7%), but was not different from noncoated seed at either irrigation amount (75.8–78.9%) (Appendix Table C.19). Among the main factors, coating effects were observed only in TF, where coated seed produced approximately 40% greater turf cover than noncoated seed at 15 DAP; however, this advantage declined to about 20% by 45 DAP, indicating a short-term benefit during early establishment (Figure. 4.4). Irrigation amount had a more consistent influence, which the higher irrigation amounts (5.1 mm d⁻¹) increased turf cover by 25 to 30% at 15 to 25 DAP in PR and by 21 to 30% at 25 to 35 DAP in TF; however, no differences were observed between irrigation amounts at 45 DAP (Figure. 4.4; Appendix Tables C.17 and C.18). Seed coating and irrigation amount did not influence turf cover in KB. Overall, greater irrigation enhanced early canopy development in PR and TF, whereas coating provided a species-specific, short-term benefit only in TF (Appendix Tables C.17 and C.18).

In Experiment 2, no two- or three-way interactions were detected for any species. Among main effects, soil type was the only consistent factor influencing turf cover (grid count), with silt loam soil producing, on average, 16 to 42% greater cover than sandy soil across all species (Figure. 4.5; Appendix Tables C.20 and C.21). Seed coating and irrigation frequency effects were not observed except at 45 DAP, daily irrigation produced 6% greater turf cover than irrigation applied every 2 d in TF, and coated seed resulted in 22% greater cover than noncoated seed in KB at 45 DAP (Appendix Tables C.20 and C.21).

In Experiment 3, grid count followed trends similar to visual turf cover across all dates, with a strong irrigation frequency $\times$ soil type interaction (Appendix Tables C.22 and C.23). Daily irrigation in silt loam increased turf cover (grid count), from 7% at 15 DAP to 67% at 45 DAP; whereas daily irrigation in sand resulted in only 2 to 15% bermudagrass cover over the same period. Extending the irrigation interval to every 3 d severely limited bermudagrass establishment, with 0% turf cover in sand and only 2 to 12% in silt loam across all dates. A seed coating $\times$ soil type interaction occurred only at 15 DAP ($P = 0.0337$), where noncoated seed in silt loam produced 6% turf cover compared with 3% for coated seed, while both coating treatments in sand remained near 1% (data not shown). Among main effects, noncoated seed produced greater turf cover (grid count) than coated seed throughout establishment (27% vs. 19% by 45 DAP). Overall, daily irrigation and silt loam soil were the major factors influencing bermudagrass establishment, whereas coating effects were small and inconsistent (Appendix Table C.22).

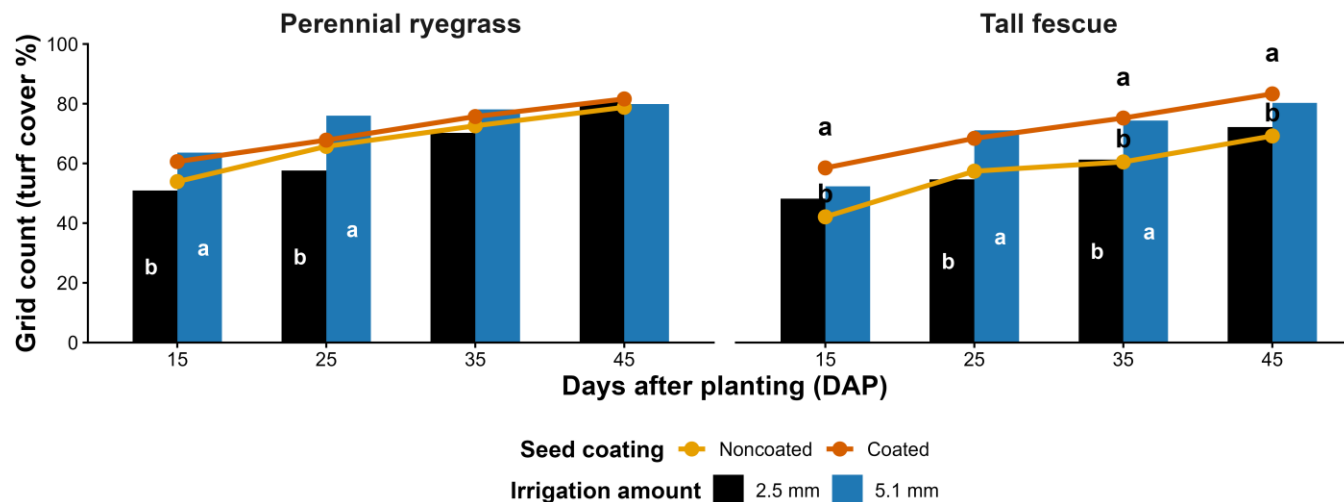


Figure 4.4. Effect of coating and irrigation amount on turf cover (%) from grid counts in perennial ryegrass and tall fescue across days after planting (DAP) in Experiment 1. *Note:* Bars represent irrigation amount (2.5 mm d⁻¹ and 5.1 mm d⁻¹), and lines represent coating treatments (coated vs. noncoated). Letters within each DAP indicate significant differences ($\alpha = 0.05$).

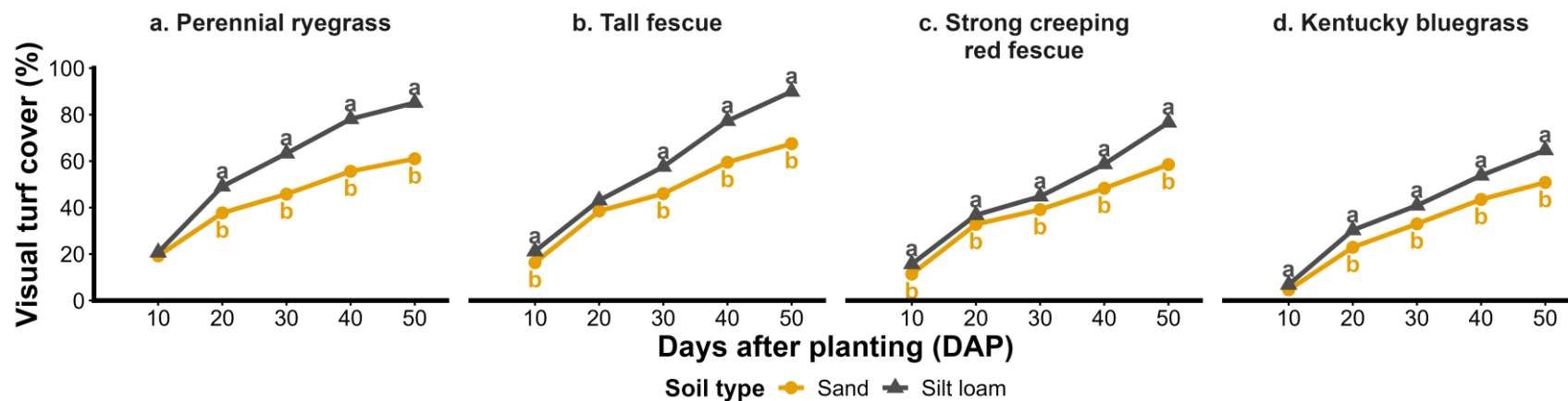


Figure 4.5. Effect of soil type on grid count (turf cover %) at 15, 25, 35, and 45 days after planting in four cool-season turfgrass species in Experiment 2. *Note:* Letters within each DAP indicate significant differences ($\alpha = 0.05$).

Discussion

Seedling emergence

Seedling emergence was not influenced by seed coating, daily irrigation amounts, or irrigation frequencies in Experiments 1 and 2, except for one instance in KB in Experiment 1, where coated seed emerged 0.5 d later than noncoated seed. This slight delay may be due to the coating acting as a minor physical barrier that slows imbibition and radicle emergence. Previous turfgrass studies have also reported inconsistent effects of seed coating on germination and establishment, with responses depending on turfgrass species, coating material, and growing conditions (Pedrini et al., 2017; Richardson & Hignight, 2010; Serena et al., 2012a, 2012b; Sochorec & Knot, 2013). In Experiments 2 and 3, soil type was the most consistent factor influencing emergence, with silt loam promoting faster seedling emergence than sand in TF, SCRF, KB, and bermudagrass. This response is likely due to greater water-holding capacity and more consistent moisture availability in finer-textured soils, whereas sand drains rapidly and dries more quickly near the soil surface (Fry & Huang, 2004; Huang, 2008). Because turfgrass seed is sown only a few millimeters deep, emergence is highly sensitive to wetting and drying cycles in the upper seed zone. As expected, daily irrigation resulted in the earlier bermudagrass seedling emergence than irrigation every 3 d, suggesting that frequent irrigation helped maintain continuous moisture around the seed, especially in sand. Overall, seedling emergence across experiments was driven by moisture availability associated with soil type and irrigation regimes, whereas seed coating had no meaningful influence under the conditions evaluated, which is similar to past findings (Richardson & Hignight, 2010; Munshaw et al., 2014; Serena et al., 2012a, 2012b).

Turf cover

Visual turf cover

Across all three Experiments, irrigation practices or soil types consistently proved to be the primary drivers of successful turfgrass establishment, while seed coating failed to provide any reliable benefits. Across the multiple grass species investigated and testing conditions, coated seeds were largely ineffective. Coating provided either negligible results, a highly inconsistent and fleeting early boost (Experiments 1 & 2), or a slight disadvantage compared to bare, noncoated seeds (Experiment 3). Any early advantage from seed coating may have been short-lived because the coating likely dissolved during the initial establishment phase. Once seedlings were established and able to access soil moisture through developing roots, coated seed may have provided little additional benefit over noncoated seed. In some cases, the coating may have served as a temporary physical barrier, resulting in negligible or slightly negative effects on turf cover (Richardson & Hignight, 2010; Serena et al., 2012a, 2012b; Pedrini et al., 2017).

As one would expect, silt loam consistently and significantly outperformed sandy soil in turfgrass establishment, resulting in much higher overall turf cover percentages (Experiments 2 & 3). This was likely because silt loam has greater water-holding capacity, which maintained more stable moisture conditions between irrigation events than rapidly draining sand (Fry & Huang, 2004; Huang, 2008). Higher irrigation amounts accelerated early growth for most species (Experiment 1). This response was likely most evident during early establishment because young seedlings have shallow root systems and depend strongly on moisture in the upper soil layer; as turfgrass matured, treatment differences likely narrowed as roots developed and plants accessed water from deeper soil layers (Huang, 2008; Braun et al., 2022a; Serena et al., 2022). For bermudagrass specifically, frequent (daily) watering was an absolute requirement; watering only

every 3 d resulted in near-total establishment failure, regardless of the soil type (Experiment 3). For the most part, variables like soil type and irrigation method worked independently. The major exception was in Experiment 3, where bermudagrass required the specific combination of both daily watering and silt loam to thrive. Irrigation every 3 d resulted in minimal turf cover across soil types, indicating that reduced irrigation frequency limited turfgrass establishment (Serena et al., 2022). Any initial differences in turf cover among irrigation treatments often diminished by 40–50 DAP as turfgrass established, likely due to more root development and access to deeper soil moisture (Braun et al., 2022a). Coating responses were inconsistent and species-specific, aligning with the trends synthesized in the review literature on seed coating research in turfgrass systems in Chapter 1. These results are consistent with previous reports that seed coatings may improve early establishment but provide minimal enhancement of later turf cover (Serena et al., 2012b). Kentucky bluegrass did not respond to irrigation amount, which may be related to its slower germination and sufficient moisture availability under both irrigation levels during emergence (Proctor et al., 2015; Serena et al., 2022). Overall, irrigation amounts consistently influenced early canopy development, whereas coating provided minimal, short-term benefits (Leinauer et al., 2010). Across experiments, visual turf cover responses were primarily driven by soil water content availability as influenced by soil types and irrigation management, whereas seed coating provided minimal benefits under these greenhouse conditions.

Percent green cover and grid count

The percent turf cover calculated from digital image analysis and grid counts confirmed the visual turf cover findings. The data for percent green cover and grid counts mirrored the visual turf cover assessments. Across all experiments, moisture availability (driven by irrigation

and soil type) was the most critical factor for canopy development. High irrigation amounts or more frequent irrigation boosted early growth (e.g., up to 54% more cover within first 30 DAP in one instance), but this advantage faded over time. Once the grass was established, lower irrigation amounts or less frequent irrigation was often sufficient to maintain the turf at ≥ 40 DAP. Seed coating provided only a fleeting, short-term advantage for two species (PR and TF) and noncoated seed performed similarly or better than coated seed in the other species. Similar to the visual turf cover data, silt loam treatments consistently outperformed sandy soil treatments due to the better water-holding capacity between irrigation treatments. Sandy soil was included in Experiments 2 and 3 to determine whether the benefits of seed coating would be more evident in this soil type than in silt loam; however, no reliable benefits of seed coating were observed.

Although percent green cover occasionally detected treatment differences not observed in visual ratings, overall trends were consistent across methods. Digital image analysis may capture small, transient differences in canopy development that are less apparent visually. These differences likely reflect the greater sensitivity of digital image analysis, which can detect small, transient variations in canopy development that are less apparent visually (Ghali et al., 2011; Richardson et al., 2001). Across all approaches, turfgrass establishment was primarily driven by moisture availability associated with irrigation and soil type, whereas seed coating provided limited and short-term, species-specific benefits aligned with previous studies (Leinauer et al., 2010; Moran et al., 2025; Newell, 1997; Newell et al., 1999; Richardson & Hignight, 2010; Serena et al., 2012b; Sochorec & Knot, 2013) and with trends summarized in the review literature on seed-coating performance in turfgrass systems in Chapter 1. The quantitative data on percent green cover and grid counts firmly support the visual observations. Proper soil moisture, achieved through good soil water-holding capacity (silt loam) and adequate irrigation

practices, is the true driver of turfgrass establishment. Based on this experiment, seed coatings offer no lasting or reliable benefits for turfgrass establishment.

Conclusions

These findings are directly relevant for turfgrass managers. Early establishment was mainly influenced by maintaining adequate soil moisture, indicating that irrigation practices were more important than the use of coated seed. Higher irrigation amounts or more frequent irrigation improved early establishment in PR, TF, SCRF, and bermudagrass, although these advantages declined as the turfgrass fully established due to a larger root system. Therefore, frequent irrigation accelerates early growth across most species, but this extra watering becomes less important once the turf is fully established. Soil texture also had a strong influence, with silt loam producing faster and more uniform turf cover than sand, likely due to its greater water-holding capacity. Seed coatings offer only inconsistent, fleeting benefits and should never be relied upon as a water-saving strategy. These findings indicate that turfgrass managers should focus their efforts and resources on optimizing irrigation practices and improving rootzone soil quality rather than relying on coated seeds.

These greenhouse studies demonstrated that soil moisture availability, influenced by irrigation and soil type, was the primary factor in early turfgrass establishment. Seed coating effects were small, species-dependent, and limited to early development, indicating that coatings are not a substitute for adequate irrigation or soil moisture management. However, this study evaluated only two coating materials under controlled greenhouse conditions. Therefore, the results may differ under field environments and different coating materials with variable weather conditions. Coating performance may also vary with different formulations, seed treatments, and

environmental stresses. However, these three experiments confirm that successful turfgrass establishment depends overwhelmingly on planting in high-quality soil (silt loam) and providing adequate, frequent irrigation, and relying on seed coating to improve or accelerate establishment is generally ineffective. Future research should evaluate a wider range of coating formulations under deficit irrigation and diverse field conditions to better understand their potential role in improving turfgrass establishment.

References

- Association of Official Seed Analysts. Volume, 1. (2016). *AOSA rules for testing seeds: Vol. 1. Principles and procedures*. Association of Official Seed Analysts.
- Barton, L., & Colmer, T. D. (2006). Irrigation and fertiliser strategies for minimising nitrogen leaching from turfgrass. *Agricultural Water Management*, 80, 160–175. <https://doi.org/10.1016/j.agwat.2005.07.011>
- Braun, R. C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022b). Review of cool-season turfgrass water use and requirements: II. Responses to drought stress. *Crop Science*, 62, 1685–1701. <https://doi.org/10.1002/csc2.20790>
- Braun, R. C., Mandal, P., Nwachukwu, E., & Stanton, A. (2024). The role of turfgrasses in environmental protection and their benefits to humans: Thirty years later. *Crop Science*, 64, 2909–2944. <https://doi.org/10.1002/csc2.21383>
- Braun, R. C., Patton, A. J., Watkins, E., Hollman, A. B., Murphy, J. A., Park, B. S., Kowalewski, A. R., & Braithwaite, E. T. (2021). Optimal fine fescue mixture seeding dates in the northern United States. *Agronomy Journal*, 113, 4413–4428. <https://doi.org/10.1002/agj2.20859>
- Braun, R.C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022a). Review of cool-season turfgrass water use and requirements: I. Evapotranspiration and responses to deficit irrigation. *Crop Science*, 62, 1661–1684. <https://doi.org/10.1002/csc2.20791>
- Colmer, T. D., & Barton, L. (2017). A review of warm-season turfgrass evapotranspiration, responses to deficit irrigation, and drought resistance. *Crop Science*, 57, S98–S110. <https://doi.org/10.2135/cropsci2016.10.0911>
- Fry, J., & Huang, B. (2004). *Applied Turfgrass Science and Physiology*. John Wiley & Sons.
- Gaussoin, R. E., & Branham B. E. (1989). Influence of cultural factors on species dominance in a mixed stand of annual bluegrass/creeping bentgrass. *Crop Science*, 29, 480–484. <https://doi.org/10.2135/cropsci1989.0011183X002900020048x>
- Ghali, I. E., Grabow, G. L., Huffman, R. L., & Miller, G. L. (2011). Comparing digital image analysis and other turf quality measurements in the evaluation of smart irrigation technologies, Doctoral dissertation, *North Carolina State University*.
- Hathcock, A. L., Dernoeden, P. H., Murray, J. J., & Wehner, D. J. (1984a). Seed germination of tall fescue and Kentucky bluegrass as affected by adhesives. *HortScience*, 19, 442–443. <https://doi.org/10.21273/HORTSCI.19.3.442>
- Hathcock, A. L., Dernoeden, P. H., Turner, T. R., & McIntosh, M. S. (1984b). Tall fescue and Kentucky bluegrass response to fertilizer and lime seed coatings. *Agronomy Journal*, 76, 879–883. <https://doi.org/10.2134/agronj1984.00021962007600060005x>

- Huang, B. (2008). Turfgrass water requirements and factors affecting water usage. *Water Quality and Quantity Issues for Turfgrass in Urban Landscapes. CAST Spec. Publ*, 27, 193–205.
- Layton, J., Munshaw, G., Stewart, B., Baldwin, B., & Philley, H. (2007). Does seed coating affect bermudagrass germination? *ASA-CSSA-SSSA Annual Meeting Abstracts*. ASA, CSSA, and SSSA, Madison, WI.
- Leinauer, B., Serena, M., & Singh, D. (2010). Seed coating and seeding rate effects on turfgrass germination and establishment. *HortTechnology*, 20, 179–185.
doi.org/10.21273/HORTTECH.20.1.179
- Madsen, M. D., Fidanza, M. A., Barney, N. S., Kostka, S. J., Badrakh, T., & McMillan, M. F. (2016). Low-dose application of nonionic alkyl terminated block copolymer surfactant enhances turfgrass seed germination and plant growth. *HortTechnology*, 26, 379–385.
doi.org/10.21273/HORTTECH.26.4.379
- Madsen, M. D., Kostka, S. J., Hulet, A., Mackey, B. E., Harrison, M. A., & McMillan, M. F. (2013). Surfactant seed coating—a strategy to improve turfgrass establishment on water repellent soils. *In International Symposium on Adjuvants for Agrochemicals*, 205–210.
- Madsen, M. D., Petersen, S., & Taylor, A. G. (2017). Seed coating compositions and methods for applying soil surfactants to water-repellent soil. *U.S. Patent No. 9,554,502*. Washington, DC: U.S. Patent and Trademark Office.
- Madsen, M. D., Zvirzdin, D. L., Roundy, B. A., & Kostka, S. J. (2014). Improving reseeding success after catastrophic wildfire with surfactant seed coating technology. *Pesticide Formulation and Delivery Systems*, 33, 44–48.
- McMillan, M., Daroub, S., Moore, K., Erickson, J., Kostka, S., & Fidanza, M. (2023). Surfactant-coated seed emergence and establishment under deficit irrigation in hydrophilic and hydrophobic soils. *Journal of Environmental Horticulture*, 41, 33–39.
<https://doi.org/10.24266/2573-5586-41.1.33>
- Moran, J., Goggi, A. S., Moore, K. J., Fei, S. Z., & Gruss, S. (2025). Improving groundcover 597 establishment through seed rate, seed ratio, and hydrophilic seed coating. *Agronomy*, 15, 1927. <https://doi.org/10.3390/agronomy15081927>
- Munshaw, G. C., Layton, J. M., Stewart, B. R., Philley, H. W., Beasley, J. S., & Lemus, R. W. (2014). The Germination responses of five bermudagrass cultivars to seed coating and temperature. *HortScience*, 49, 1225–1229. <https://doi.org/10.21273/HORTSCI.49.9.1225>
- Newell, A. J. (1997). Effect of different seed treatments and coatings on the germination and establishment of four grass species. *Journal of Turfgrass Science*, 73, 67–72.
- Newell, A. J., Hart-Woods, J. C., & Crossley, F. M. (1999). Investigation of the effects of Fortiva seed treatment on the establishment of different grass species and 607 mixtures. *Journal of Turfgrass Science*, 75, 89–99.

- Paravar, A., Piri, R., Balouchi, H., & Ma, Y. (2023). Microbial seed coating: An attractive tool for sustainable agriculture. *Biotechnology Reports*, 37, e00781. <https://doi.org/10.1016/j.btre.2023.e00781>
- Pedrini, S., Merritt, D. J., Stevens, J., & Dixon, K. (2017). Seed coating: Science or marketing spin?. *Trends in Plant Science*, 22, 106–116. <https://doi.org/10.1016/j.tplants.2016.11.002>
- Proctor, C. A., Weisenberger, D. V., & Reicher, Z. J. (2015). Kentucky bluegrass and perennial ryegrass mixtures for establishing Midwest lawns. *HortScience*, 50, 137–140. <https://doi.org/10.21273/HORTSCI.50.1.137>
- Richardson, M. D., & Hignight, K. W. (2010). Seedling emergence of tall fescue and Kentucky bluegrass, as affected by two seed coating techniques. *HortTechnology*, 20, 415–417. <https://doi.org/10.21273/HORTTECH.20.2.415>
- Richardson, M. D., Karcher, D. E., & Purcell, L. C. (2001). Quantifying turfgrass cover using digital image analysis. *Crop Science*, 41, 1884–1888. <https://doi.org/10.2135/cropsci2001.1884>
- Rocha, I., Ma, Y., Souza-Alonso, P., Vosátka, M., Freitas, H., & Oliveira, R. S. (2019). Seed coating: a tool for delivering beneficial microbes to agricultural crops. *Frontiers in Plant Science*, 10, 1357. <https://doi.org/10.3389/fpls.2019.01357>
- Serena, M., Leinauer, B., Sallenave, R., Schiavon, M., & Maier, B. (2012a). Media selection and seed coating influence germination of turfgrasses under salinity. *HortScience*, 47, 116–120. <https://doi.org/10.21273/HORTSCI.47.1.116>
- Serena, M., Leinauer, B., Sallenave, R., Schiavon, M., & Maier, B. (2012b). Turfgrass establishment from polymer-coated seed under saline irrigation. *HortScience*, 47, 1789–1794. <https://doi.org/10.21273/HORTSCI.47.12.1789>
- Serena, M., Leinauer, B., Velasco-Cruz, C., & Sevostianova, E. (2022). Optimizing frequency and amount of irrigation needed to establish cool-season turfgrasses. *Agronomy Journal*, 114, 1851–1858.
- Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, 52, 591–611. <https://doi.org/10.1093/biomet/52.3-4.591>
- Sochorec, M., & Knot, P. (2013). The effect of fertilizer seed coating on the germinating capacity and initial development of some turf grass species and white clover. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 60, 23.
- United States Department of Agriculture, Natural Resources Conservation Service. (2011, November). *Calculating Seeding Rates for Conservation Plantings* (Plant Materials Technical Note No: TX-PM-12-02).

Wynne, T., & Devitt, D. (2020). Evapotranspiration of urban landscape trees and turfgrass in an arid environment: potential trade-offs in the landscape. *HortScience*, 55, 1558–1566.
<https://doi.org/10.21273/HORTSCI15027-20>

Chapter 5 - Effects of Seed Coating and Irrigation Frequency on Turfgrass Establishment in the Field

Abstract

Turfgrass systems provide numerous ecosystem services but often require supplemental irrigation during establishment because of water demands for seed germination and early growth. While common in agriculture, seed coating is an under-researched technique in turfgrass systems that has the potential to enhance germination under limited water conditions and warrants further exploration. Two field experiments were conducted under an automated rainout shelter in Manhattan, KS, during the summer and autumn of 2024, and repeated in 2025, to evaluate the effects of seed coating and irrigation frequency on turfgrass establishment. Species included tall fescue (*Festuca arundinacea* Schreb.), Kentucky bluegrass (*Poa pratensis* L.), and bermudagrass [*Cynodon dactylon* (L.) Pers.]. Experiments were arranged as a randomized complete block design with two factors: seed coating [coated vs. noncoated], and irrigation frequency [every 2 days vs. every 4 days]. Coated seed contained limestone-based material, fungicide, or nutrient-based additives, depending on seed source. Measurements included seedling emergence, visual turf cover, and population counts. Across both experiments, seed coating did not improve seedling emergence or turf cover. In Experiment 1 (summer), turf cover remained <5% across species by 35 days after planting (DAP), indicating summer heat stress and rapid soil drying limited establishment. In Experiment 2 (autumn), irrigation every 2 days increased turf cover by maintaining soil moisture, whereas irrigation every 4 days reduced turf cover by 65 to 90% across both species by 45 DAP. Overall, turfgrass managers should prioritize favorable planting timing and adequate soil moisture through proper irrigation management during establishment rather than relying on seed coating to improve turfgrass establishment.

Introduction

Turfgrass systems provide a range of ecosystem services beyond their recreational and aesthetic value, including soil stabilization, reduced runoff, water filtration, improved water quality, evaporative cooling, soil carbon sequestration, support for biodiversity, and additional environmental and societal contributions to human well-being (Braun et al., 2024).

Establishment is one of the most sensitive stages in turfgrass development because seed germination and seedling growth depend strongly on favorable moisture and temperature conditions near the soil surface (Braun et al., 2020, 2021; Reicher et al., 2000). During this period, supplemental irrigation is often needed to maintain sufficient soil moisture for germination and seedling establishment, whereas limited moisture can delay emergence, produce weak seedlings, and increase the risk of seed desiccation and stand loss (Braun et al., 2022b; Huang, 2008). Therefore, irrigation management during establishment plays a critical role in promoting seedling survival, uniform turfgrass cover, and rapid canopy development.

Water-use behavior varies widely among turfgrass species because cool- and warm-season grasses differ in physiology, growth habit, rooting characteristics, and adaptation to temperature and water stress (Braun et al., 2022a, 2022b; Colmer & Barton, 2017). Cool-season turfgrass species such as tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] (TF) and Kentucky bluegrass (*Poa pratensis* L.) (KB) are commonly used in lawns, sports fields, golf, and other managed turf areas, and demand frequent irrigation because of their C₃ photosynthetic pathway, which makes these turfgrasses sensitive to heat and drought stress (Fry & Huang, 2004; Severmutlu et al., 2011). In contrast, warm-season species such as bermudagrass [*Cynodon dactylon* (L.) Pers.] or buffalograss [*Bouteloua dactyloides* (Nutt.) J.T. Columbus] are generally better adapted to summer heat and

can use water more efficiently; however, successful establishment still requires adequate moisture during germination and early seedling growth. Although water-use demands vary among species and cultivars, demands are also strongly influenced by environmental conditions (Braun et al., 2022a, 2022b). This variability is especially important under field conditions, where temperature, rainfall, and soil properties fluctuate in ways that are difficult to replicate in controlled environments.

Increasing pressure on water resources has created a need for practices that reduce irrigation demand while still promoting successful turfgrass establishment and maintenance, especially in arid and semi-arid regions (Wynne & Devitt, 2020). This is particularly important where urban landscapes compete with agricultural, industrial, and residential water use. Seed coating has been used as one potential strategy to improve seedling establishment under stressful conditions by modifying the seed microenvironment (Halmer, 2008, Svejcar et al., 2022). Although widely used in agricultural and horticultural systems, seed coating remains an emerging concept in the turfgrass industry, with limited turfgrass-specific research available to support its claims. Coating materials may include polymers, surfactants, nutrients, binders, fillers, growth regulators, or other additives designed to improve water availability, seed handling, germination, or early seedling vigor (Paravar et al., 2023; Rocha et al., 2019), and see Chapter 1 for more detail. However, the effectiveness of seed coating in turfgrass systems remains unclear under water-limited and other abiotic stress conditions.

Previous turfgrass studies have reported mixed responses to seed coating. Some polymer- and surfactant-based coatings have improved establishment, soil water availability, or early turf cover under limited irrigation or challenging soil conditions, such as hydrophobic soils (Leinauer et al., 2010; Madsen et al., 2013, 2014, 2016, 2017). Similarly, surfactant-coated perennial

ryegrass (*Lolium perenne* L.) has shown potential to maintain establishment even at reduced seeding rates (McMillan et al., 2023). Earlier field studies reported neutral or positive effects of adhesive-based limestone and fertilizer coatings on KB and TF establishment (Hathcock et al., 1984a, 1984b). However, other studies have reported delayed establishment or limited benefits from coated seed in cool- and warm-season turfgrass species (Layton et al., 2007; Munshaw et al., 2014; Richardson & Hignight, 2010; Serena et al., 2012a, 2012b). These inconsistent reports likely reflect the narrow range of species and coating materials examined to date, as well as limited disclosure of coating composition by manufacturers because of proprietary restrictions. Currently, fewer than 20 peer-reviewed studies have addressed seed coating in turfgrass over the past three decades, creating a gap between industry claims and publicly available research. Given ongoing pressure to conserve water, additional field-based evaluation is needed to determine whether seed coatings can improve establishment efficiency under extended irrigation intervals. Therefore, the objectives of these field experiments were to evaluate seedling emergence and turfgrass establishment of cool- and warm-season turfgrass species as influenced by seed coating and irrigation frequency during two establishment seasons, summer and autumn.

Materials and Methods

Experiment design and management

Two field experiments were conducted under an automated rainout shelter (12 × 12 m) at the Rocky Ford Turfgrass Research Center at Kansas State University in Manhattan, KS (39° 13' 53" N; 96° 34' 51" W) (Appendix Figure D.1). Experiment 1 (i.e., summer) was conducted from 9 July to 13 August in 2024 and repeated in 2025 (35-day duration). Experiment 2 (i.e., autumn) was conducted from 9 September to 24 October 2024 and repeated from 4 September to 19

October 2025 (45-day duration). Air temperature and relative humidity were obtained from the Rocky Ford weather station in Manhattan, KS, and summarized for each experimental period in the Results and Discussion section. Experiment 1 included two cool-season turfgrass species, TF and KB, and one warm-season turfgrass species, bermudagrass. Experiment 2 included only TF and KB. For each species, coated and noncoated seeds from the same seed lot were evaluated. Information on species, cultivars or blends, coating composition, and seed companies' is presented in Table 5.1.

Table 5.1. Species, cultivars or blends, coating composition, and seed companies' information.

Species	Cultivar/Blend	Coating composition	Company
Experiment 1			
Tall fescue	RTF (TF blend) 'Barmesh' 'Flame' 'Zion' 'Bonfire'	Noncoated or coated Coating name and information for both TF & KB: Yellow Jacket Includes: Limestone base ($\approx 50\%$ of coating weight; inert material + dried actives)	Barenbrug USA (Tangent, OR, USA)
Kentucky bluegrass	HGT (KB blend) 'Barserati' 'Barvette' 'Barrister' 'Barimpala' 'Barrari' 'Barduke'	Starch-based superabsorbent Apron XL fungicide Fertility treatment	
Bermudagrass	Rio	Noncoated or coated Coating name: WaterGard Includes: 50% coating material STEP UP nutrient-based seed treatment additive Apron XL fungicide Blue colorant	Mountain View Seeds (Salem, OR, USA)
Experiment 2			
Tall fescue	----- same as Experiment 1 -----		
Kentucky bluegrass	Merit	Noncoated or coated Coated with a 1% limestone super-absorbent	Mountain View Seeds (Salem, OR, USA)

Experiments 1 and 2 were arranged as randomized complete-block designs with four and three replications, respectively, and were repeated across two years. Treatments included two seed coating types (coated vs. noncoated) and two irrigation frequencies (irrigation every 2 days vs. every 4 days) under field conditions. In both experiments, each plot measured 0.91×0.91 m (3×3 ft), with a 1.22×0.91 m (4×3 ft) buffer area between blocks (replications). The soil at the site was Chase silty clay loam containing 30% sand, 52% silt, and 18% clay, with a pH of 7.4, and 4.8% organic matter.

Seeding

A starter fertilizer (18–24–12, The Andersons, Maumee, OH, USA) was applied at 203 kg product ha⁻¹ (37 kg N ha⁻¹ and 49 kg P₂O₅ ha⁻¹) in both experiments. No additional fertilizer was applied after planting. Seed was applied manually by hand and lightly incorporated with a leaf rake after seeding to promote seed-to-soil contact (Appendix Figure D.2 and D.3).

To ensure uniform seeding across all treatments, seeding rates were calculated on a pure live seed (PLS) basis using standard laboratory procedures (Association of Official Seed Analysts [AOSA], 2016; USDA NRCS, 2011). Seed purity was obtained from seed labels of each turfgrass species, and germination tests were conducted within 3 months of each experiment to determine PLS for each species. The thousand-seed count weight was also determined for each species and coating type. These counts were to be combined with PLS to calculate seed weights per plot, corresponding to the equivalent 2 PLS cm⁻² for each species (Table 5.2). This method ensured that each plot received the same number of viable seeds, regardless of whether the seeds were coated or noncoated, which varied in weight.

Table 5.2. Pure live seed (PLS) rates and seed weight used for turfgrass species in Experiments 1 and 2.

Experiments	Species	Cultivar	Coating	Seeding rate PLS cm ⁻²	Seed weight (g m ⁻²)	
					(2024)	(2025)
Experiment 1	Tall fescue	RTF (TF blend)	Noncoated	2	47.1	50.0
			Coated	2	109.6	116.5
	Kentucky bluegrass	HGT (KB blend)	Noncoated	2	7.2	7.6
			Coated	2	20.1	21.1
	Bermudagrass	Rio	Noncoated	2	5.0	5.3
			Coated	2	11.6	12.3
Experiment 2	Tall fescue	RTF (TF blend)	Noncoated	2	47.1	51.2
			Coated	2	109.5	113.3
	Kentucky bluegrass	Merit	Noncoated	2	7.0	7.2
			Coated	2	19.5	19.1

Note: Seed weight (g m⁻²) was adjusted each year based on seed lot germination percentage to maintain the target PLS seeding rate.

Irrigation

All plots were irrigated immediately after seeding to saturate the soil profile, and then irrigation treatments began the following day. Both experiments included two irrigation frequencies: irrigation every 2 days and every 4 days. In Experiment 1, each irrigation event applied 8.9 mm of water, equivalent to 7.4 L plot⁻¹. In Experiment 2, the irrigation amount was 6.4 mm, equivalent to 5.3 L plot⁻¹. Irrigation amounts differed between experiments based on seasonal temperature and seasonal evapotranspiration demand. Irrigation treatments were applied manually with a hose and a water meter. To eliminate rainfall as a source of variability, the rainout shelter automatically deployed to cover the experimental area in less than 1 min after detecting 0.254 mm of precipitation and retracted 1 h after rainfall ceased.

Data collection

Data collection methods were the same in both experiments. The date of seedling emergence in each plot was recorded when the tip of the first leaf appeared above the soil surface

similar to the methodology of Braun et al. (2021). Plots were monitored daily until seedling emergence was observed in all plots, and the average number of days to first emergence was calculated. Visual turfgrass cover (0 to 100%) was assessed every 5 days from 5 to 35 days after planting (DAP) in Experiment 1, and up to 45 DAP in Experiment 2. Percent green cover (0 to 100%) was measured using digital image analysis (Richardson et al., 2001) every 5 days from 5 to 35 or 45 DAP in both experiments. Images were taken with a Nikon Z30 digital camera (Nikon Inc., Japan) mounted on a customized lightbox measuring $60 \times 60 \times 50$ cm (L $\times$ W $\times$ H). Manual camera settings were f/4.5, ISO 125, and 1/80 s shutter speed. Images were 3712×5668 pixels at 300 dpi. Images were analyzed using Turf Analyzer 1.0.4 (Green 155 Research Services, LLC, Fayetteville, AR) with threshold settings hue: 70-170, saturation: 5-100, and brightness: 0-100 and a frame threshold settings of hue: 171-256, saturation: 25-100%, brightness: 0-100% to calculate green pixels relative to non-green area (e.g., soil). Grid counts (turf cover) were collected from 10 to 35 or 45 DAP with 10- or 15-day intervals (Experiment 1 and 2, respectively) using a modified vertical point quadrat method (Braun et al., 2020, 2021; Gaussoin & Branham, 1989), where a 1×1 m frame was set above the plot with a filament grid of 100 intersections. The total number of instances of a turfgrass shoot present under each intersection was recorded for each plot and expressed as a percentage of turfgrass cover (Appendix Figure D.4).

Data analysis

Analysis of variance was conducted for seedling emergence, visual turf cover, percent green cover, and grid counts using the GLIMMIX procedure in SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Main effects and interactions were considered significant at $\alpha = 0.05$. Species was not considered a treatment factor in either experiment because it was not an

objective of these experiment; therefore, treatment effects were analyzed separately within each species.

For seedling emergence in Experiment 1, the mean number of days to first visible seedling emergence was calculated. In addition, the number of plots with visible emergence was summarized from the total number of plots per species ($n = 16$), as several plots did not germinate and emerge. In Experiment 2, all plots had germination and emergence; therefore, mean values for seedling emergence were calculated and summarized in the Results and Discussion section, and statistical analysis was not conducted for seedling emergence (Table 5.4). Data from the two runs of each experiment were pooled for analysis because the run $\times$ treatment interactions were not significant. The Shapiro-Wilk test was used to assess residual normality (Shapiro & Wilk, 1965). For both experiments, data including visual turf cover, percent green cover, and grid count were arcsine square-root transformed prior to analysis to meet the assumptions of normality; means were back-transformed for interpretation. Means were separated using Fisher's protected LSD test ($\alpha = 0.05$) when F -tests were significant ($P \leq 0.05$) within each species.

Results and Discussion

Weather conditions during establishment

Mean air temperature was higher during Experiment 1, ranging from 25.1 to 26.0 °C, compared with 19.4 to 20.7 °C during Experiment 2 (Table 5.3). Maximum air temperature reached 39.0 and 38.4 °C during Experiment 1 in 2024 and 2025, respectively, indicating that summer seeding exposed seedlings to greater heat stress during establishment. These warmer conditions likely increased soil surface drying and affected the turfgrass establishment,

especially for cool-season turfgrasses. In contrast, the lower mean air temperatures during Experiment 2 provided a more favorable autumn seeding window, which likely contributed to faster emergence and greater turf cover compared with Experiment 1 across both years.

Table 5.3. Air temperature (°C) and relative humidity (%) during Experiments 1 and 2 in 2024 and 2025.

Experiment	Year	Air temperature (°C)			Relative humidity (%)		
		Min	Max	Mean	Min	Max	Mean
Experiment 1 (Summer)	2024	11.9	39.0	25.1	52.2	93.1	70.0
	2025	14.7	38.4	26.0	54.1	89.3	72.6
Experiment 2 (Autumn)	2024	-3.0	36.1	19.4	31.4	82.2	56.0
	2025	6.7	34.5	20.7	43.0	92.6	70.8

Note: Air temperature (°C) and relative humidity (%) were obtained from the Rocky Ford weather station in Manhattan, KS, and summarized as minimum, maximum, and mean values for each experimental period.

Seedling emergence

Seedling emergence varied among experiments, species, and irrigation-frequency treatments (Table 5.4). In Experiment 1, seedling emergence was inconsistent, with several plots showing no visible emergence during the experiment. Among the plots with seedling emergence, mean seedling emergence time ranged from 18.8 to 19.8 days for TF, 20.0 to 27.2 days for KB, and 18.8 to 22.1 days for bermudagrass across irrigation frequency treatments. A higher number of bermudagrass plots exhibited seedling emergence, 24 out of 32 bermudagrass plots, compared with TF (14 of 32 TF plots) and KB (7 out of 32 KB plots), indicating lower emergence success for the cool-season species in Experiment 1. This is not surprising, since bermudagrass is a C₄ species and can still achieve acceptable germination at warmer temperatures compared with the C₃ species of TF and KB (Braun et al., 2021; Patton et al., 2004; Reicher et al., 2000). Air temperatures reached 39.0 and 38.4 °C during Run 1 and Run 2, respectively in Experiment 1. Seed coating did not appear to influence seedling emergence across species.

In Experiment 2, all plots exhibited seedling emergence (Table 5.4). Tall fescue and KB exhibited faster seedling emergence earlier than in Experiment 1, most likely due to more favorable environmental conditions. Mean air temperature was lower during Experiment 2 than Experiment 1, ranging from 19.4 to 20.7 °C compared with 25.1 to 26.0 °C, respectively. As expected, more frequent irrigation generally hastened seedling emergence, with TF emerging at 7.7 days under every 2 days irrigation compared with 11.8 days under every 4 days irrigation. Similarly, KB emerged at 13.8 days under every 2 days irrigation compared with 22.4 days under every 4 days irrigation frequency.

Overall, seedling emergence was slower and less consistent in Experiment 1 than in Experiment 2 due to more heat stress during the summer months. Slower and less seedling emergence in Experiment 1 was likely associated with less favorable establishment conditions, including higher temperature stress and greater evaporative demand, which caused the soil surface and seed to dry more often during early establishment. These conditions likely reduced seed survival and delayed seedling emergence, especially for the cool-season species (Sun et al., 2024). In contrast, Experiment 2 was conducted during an autumn establishment period, which is more favorable for cool-season turfgrasses (Braun et al., 2021; Patton et al., 2004; Reicher et al., 2000). Across both experiments, irrigation frequency appeared to have a greater influence on seedling emergence timing than seed coating, whereas seed coating had little effect on the mean number of days to seedling emergence. These findings are consistent with several previous studies (Layton et al., 2007; Munshaw et al., 2014; Richardson & Hignight, 2010; Serena et al., 2012b; Sochorec & Knot, 2013).

Table 5.4. Mean seedling emergence time of turfgrass species as influenced by seed coating and irrigation frequency in Experiments 1 and 2.

	Seedling emergence (days)				
	Experiment 1			Experiment 2	
	Tall fescue	Kentucky bluegrass	Bermudagrass	Tall fescue	Kentucky bluegrass
Seed coating					
Coated	18.9 (7)	25.8 (4)	19.5 (12)	9.7	17.4
Noncoated	19.3 (7)	24.3 (3)	20.3 (12)	9.8	18.8
Irrigation frequency					
Every 2 days	18.8 (10)	27.2 (5)	18.8 (16)	7.7	13.8
Every 4 days	19.8 (4)	20.0 (2)	22.1 (8)	11.8	22.4

Note: Values represent mean days to first visible seedling emergence. Values in parentheses indicate the number of plots emerged in Experiment 1, where the total number of potential plots for each species was 16. In Experiment 1, means were calculated only from plots with emergence. In Experiment 2, all plots had seedling emergence. Data were summarized descriptively; statistical analysis was not conducted due to missing data (plots) with no seedling emergence. Comparisons were made within each species and experiment.

Turf cover

Visual turf cover

No significant seed coating $\times$ irrigation frequency interaction was observed for visual turf cover in either Experiment 1 or 2 (Tables 5.5 and 5.6). In Experiment 1, visual turf cover remained less than 5% across all three species and rating dates (Table 5.5). Both cool-season species, TF and KB, exhibited minimal establishment, with turf cover remaining below 1% through 35 DAP where TF emergence began by 20 DAP, while KB emergence was not observed until 30 DAP. Bermudagrass turf cover increased from 0.4 or 0.5% at 20 DAP to 3.4 to 4.7% at 35 DAP across coating treatments. However, seed coating and irrigation frequency did not significantly affect visual turf cover for any species or rating date in Experiment 1 indicating that seed coating did not enhance turfgrass establishment under either irrigation regime for any of the three species studied.

In Experiment 2, irrigation frequency was the major factor influencing visual turf cover, which increased over time for both TF and KB (Table 5.6). For TF, irrigation every 2 days resulted in greater turf cover than irrigation every 4 days, increasing from 9.3% at 15 DAP to 75.1% at 45 DAP, compared with 1.5 to 28.6% under irrigation every 4 days. Similarly, KB irrigated every 2 days resulted in greater turf cover and reached 17.5% cover at 45 DAP, whereas KB irrigated every 4 days reached only 3.8% cover. Seed coating yielded no observable impact on turfgrass establishments, measured by visual turf cover, of either species in Experiment 2.

The limited turf cover observed in Experiment 1 was likely associated with the warmer temperatures and unfavorable establishment conditions of the summer seeding period. Tall fescue and KB are cool-season species and are generally less adapted to establishment under high summer temperatures compared with warm-season species (Braun et al., 2021; Patton et al., 2004; Reicher et al., 2000; Severmutlu et al., 2011). Although seed coating was expected to improve establishment under stressful conditions, seed coating had no influence on turfgrass establishment of multiple species in either study. Bermudagrass had greater turf cover than TF and KB; however, turf cover still remained below 5% by 35 DAP. This suggests that the irrigation frequency treatments may not have provided sufficient moisture to support rapid germination and early turfgrass development during summer. Seeding during this time will likely require daily irrigation or even more frequent (Christians et al., 2017). One hypothesis was that seed coating would provide a benefit under less frequent irrigation, but no such advantage was observed.

In contrast, Experiment 2 was seeded during a more favorable autumn establishment window for *C₃* species. During this period, soil temperatures were likely warm enough to support germination, while air temperatures were more favorable for TF and KB seedling development.

As a result, both cool-season species were established successfully than in Experiment 1, particularly under irrigation every 2 days. Similar to Experiment 1, the stronger response to more frequent irrigation indicates that adequate soil moisture during the first few weeks after planting was critical for early turfgrass establishment and canopy development (Serena et al., 2022). Also similar to Experiment 1, seed coating had no influence on turfgrass establishment during an autumn seeding period (i.e., visual turf cover), suggesting that early establishment was influenced more by irrigation frequency and seasonal planting conditions than by seed coating. These results align with previous findings where seed coating had minimal effects on germination and turf cover (Layton et al., 2007; Munshaw et al., 2014; Richardson & Hignight, 2010; Serena et al., 2012b; Sochorec & Knot, 2013).

Percent green cover and grid count

Quantitative assessments of turfgrass establishment, including percent green cover and grid count, followed similar patterns as visual turf cover in both experiments (Tables 5.7, 5.8, 5.9 and 5.10). These findings indicate that moisture availability (i.e., frequency of irrigation) and establishment timing (i.e., time of the year) had greater influence on turfgrass establishment than seed coating. Digital image analysis and grid counts occasionally detected small differences that were less apparent in visual ratings. Regardless, overall treatment trends were consistent across turf cover assessment methods, which is consistent with past reports (Ghali et al., 2011).

Table 5.5. Effects of seed coating and irrigation frequency on visual turf cover (%) of turfgrass species (cool- and warm- season) at 10, 20, 30, and 35 days after planting (DAP) in Experiment 1.

	Visual turf cover (%)											
	Tall fescue				Kentucky bluegrass				Bermudagrass			
	10 DAP	20 DAP	30 DAP	35 DAP	10 DAP	20 DAP	30 DAP	35 DAP	10 DAP	20 DAP	30 DAP	35 DAP
Seed coating												
Coated	—	0.4	0.5	0.6	—	—	0.1	0.1	—	0.4	2.0	3.4
Noncoated	—	0.1	0.2	0.2	—	—	0.1	0.1	—	0.5	3.3	4.7
Irrigation frequency												
Every 2 days	—	0.4	0.4	0.5	—	—	0.1	0.1	—	0.5	2.5	4.5
Every 4 days	—	0.1	0.3	0.3	—	—	0.1	0.1	—	0.4	2.8	3.6
<i>p</i> value												
Seed coating	—	0.1313	0.4200	0.3810	—	—	0.8900	0.7521	—	0.7300	0.7000	0.9404
Irrigation frequency	—	0.1313	0.4954	0.5730	—	—	0.8900	0.8923	—	0.4400	0.4000	0.2501
Seed coating × Irrigation frequency	—	0.4750	0.2430	0.3920	—	—	0.9200	0.8618	—	0.7200	0.2300	0.2495

Note: Means within a column of each main effect followed by a common letter or no letters are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Abbreviation: DAP = days after planting; Em dash (—) indicates that no visual turf cover was observed; therefore, data were not analyzed.

Table 5.6. Effects of seed coating and irrigation frequency on visual turf cover (%) of turfgrass species (cool-season) at 15, 25, 35, and 45 days after planting (DAP) in Experiment 2.

	Visual turf cover (%)							
	Tall fescue				Kentucky bluegrass			
	15 DAP	25 DAP	35 DAP	45 DAP	15 DAP	25 DAP	35 DAP	45 DAP
Seed coating								
Coated	4.9	16.8	30.6	49.8	0.3	2.8	5.2	11.8
Noncoated	5.9	18.1	31.9	53.8	0.3	1.3	5.1	9.6
Irrigation frequency								
Every 2 days	9.3 a	26.5 a	45.8 a	75.1 a	0.7 a	3.6 a	8.8 a	17.5 a
Every 4 days	1.5 b	8.3 b	16.7 b	28.6 b	0.0 b	0.6 b	1.4 b	3.8 b
<i>p</i> value								
Seed coating	0.9119	0.6152	0.7973	0.3919	0.7813	0.2922	0.8534	0.5344
Irrigation frequency	0.0031	<.0001	<.0001	<.0001	0.0199	0.0075	<.0001	0.0002
Seed coating × Irrigation frequency	0.9191	0.4498	0.7782	0.9186	0.7813	0.8187	0.2692	0.3833

Note: Means within a column of each main effect followed by a common letter or no letters are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$); Abbreviation: DAP = days after planting.

Table 5.7. Effects of seed coating and irrigation frequency on percent green cover (%) of turfgrass species (cool- and warm- season) at 10, 20, 30, and 35 days after planting (DAP) in Experiment 1.

	Percent green cover (%)											
	Tall fescue				Kentucky bluegrass				Bermudagrass			
	10 DAP	20 DAP	30 DAP	35 DAP	10 DAP	20 DAP	30 DAP	35 DAP	10 DAP	20 DAP	30 DAP	35 DAP
Seed coating												
Coated	0.1	0.1	0.1	0.3	0.0	0.0	0.1	0.3	0.0	0.2	3.2	6.2
Noncoated	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.5	6.5	9.5
Irrigation frequency												
Every 2 days	0.0	0.1	0.1	0.3	0.0	0.0	0.1	0.3	0.0	0.2	5.4	11.0
Every 4 days	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.4	4.3	4.7
<i>p value</i>												
Seed coating	0.1998	0.0833	0.6634	0.7443	0.5875	0.8210	0.6153	0.3872	0.8886	0.3448	0.7640	0.8270
Irrigation frequency	0.1850	0.2053	0.6310	0.7920	0.1845	0.5839	0.1745	0.0848	0.3908	0.7204	0.3448	0.1167
Seed coating × Irrigation frequency	0.7426	0.5399	0.3456	0.6755	0.7051	0.1600	0.1352	0.2856	0.5641	0.2384	0.2990	0.3621

Note: Means within a column of each main effect followed by a common letter or no letters are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Abbreviation: DAP = days after planting; Percent green cover was quantified from digital images using Turf Analyzer software. Values of 0.0 indicate green cover was observed as zero or rounded to 0.0%; therefore, data were included in the analysis.

Table 5.8. Effects of seed coating and irrigation frequency on percent green cover (%) of turfgrass species (cool-season) at 15, 25, 35, and 45 days after planting (DAP) in Experiment 2.

	Percent green cover (%)							
	Tall fescue				Kentucky bluegrass			
	15 DAP	25 DAP	35 DAP	45 DAP	15 DAP	25 DAP	35 DAP	45 DAP
Seed coating								
Coated	1.6	9.8	29.8	47.5	0.3	0.5	2.9	8.1
Noncoated	1.8	9.8	30.9	50.4	0.4	0.3	1.2	4.0
Irrigation frequency								
Every 2 days	3.0 a	18.1 a	51.8 a	72.6 a	0.5	0.7 a	3.8 a	11.0 a
Every 4 days	0.4 b	1.5 b	8.9 b	25.3 b	0.2	0.1 b	0.3 b	1.1 b
<i>p</i> value								
Seed coating	0.9516	0.9228	0.8988	0.7622	0.7462	0.7322	0.4723	0.337
Irrigation frequency	0.0091	<.0001	<.0001	<.0001	0.2961	0.0314	0.0119	0.0031
Seed coating × Irrigation frequency	0.8893	0.8903	0.7446	0.5351	0.7273	0.9123	0.7753	0.7993

Note: Means within a column of each main effect followed by a common letter or no letters are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$); Abbreviation: DAP = days after planting.

Table 5.9. Effects of seed coating and irrigation frequency on grid count (turf cover %) of turfgrass species (cool- and warm- season) at 10, 20, 30, and 35 days after planting (DAP) in Experiment 1.

	Grid count (turf cover %)											
	Tall fescue				Kentucky bluegrass				Bermudagrass			
	10 DAP	20 DAP	30 DAP	35 DAP	10 DAP	20 DAP	30 DAP	35 DAP	10 DAP	20 DAP	30 DAP	35 DAP
Seed coating												
Coated	—	1.1	1.1	1.3	—	—	0.1	0.3	—	0.9	1.9	5.3
Noncoated	—	0.0	0.2	0.3	—	—	0.1	0.1	—	1.7	4.1	8.6
Irrigation frequency												
Every 2 days	—	0.9	1.1	1.1	—	—	0.1	0.3	—	1.9	3.4	8.8
Every 4 days	—	0.1	0.3	0.4	—	—	0.1	0.1	—	0.7	2.6	5.1
<i>p</i> value												
Seed coating	—	0.1300	0.3400	0.4200	—	—	0.4817	0.4451	—	0.7800	0.4500	0.6400
Irrigation frequency	—	0.4000	0.4400	0.4200	—	—	0.4817	0.4451	—	0.1400	0.1300	0.0500
Seed coating × Irrigation frequency	—	0.4000	0.2200	0.4200	—	—	0.0420	0.4451	—	0.6400	0.3200	0.5400

Note: Means within a column of each main effect followed by a common letter or no letters are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Abbreviation: DAP = days after planting; Em dash (—) indicates that no visual turf cover was observed; therefore, data were not analyzed. Grid count was determined using a 100-intersection grid, with the number of turfgrass shoots present under each intersection recorded for each plot and expressed as a percentage of turfgrass cover.

Table 5.10. Effects of seed coating and irrigation frequency on grid count (turf cover %) of turfgrass species (cool-season) at 15, 25, 35, and 45 days after planting (DAP) in Experiment 2.

	Grid count (turf cover %)							
	Tall fescue				Kentucky bluegrass			
	15 DAP	25 DAP	35 DAP	45 DAP	15 DAP	25 DAP	35 DAP	45 DAP
Seed coating								
Coated	14.6	20.6	31.0	49.8	1.6	1.8	5.7	10.8
Noncoated	15.8	22.0	36.6	55.3	1.1	1.3	5.6	10.3
Irrigation frequency								
Every 2 days	25.4 a	34.2 a	50.5 a	73.8 a	2.5 a	3.0 a	10.1 a	18.3 a
Every 4 days	5.0 b	8.4 b	17.1 b	31.3 b	0.2 b	0.2 b	1.2 b	2.9 b
<i>p</i> value								
Seed coating	0.4863	0.6976	0.2793	0.3433	0.9969	0.9764	0.7394	0.5680
Irrigation frequency	<.0001	<.0001	<.0001	<.0001	0.0073	0.0062	<.0001	<.0001
Seed coating × Irrigation frequency	0.3829	0.6132	0.9860	0.8143	0.5110	0.5282	0.1027	0.0877

Note: Means within a column of each main effect followed by a common letter or no letters are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$); Abbreviation: DAP = days after planting. Grid count was determined using a 100-intersection grid, with the number of turfgrass shoots present under each intersection recorded for each plot and expressed as a percentage of turfgrass cover.

Conclusions

These two field experiments showed that turfgrass establishment was strongly influenced by maintaining adequate soil moisture, suggesting that optimum irrigation frequency is more important than seed coating. In Experiment 1, seeding turfgrass species in summer resulted in poor and inconsistent emergence, particularly for the cool-season species. This aligns with past best management practices. These results demonstrate that seed coating cannot overcome such temperature and moisture limitations. Ultimately, environmental conditions and irrigation management dictate establishment success far more than seed treatments. Summer planting of turfgrass seed resulted in poor cover (<5%) due to heat stress and rapid soil drying, with seed coating providing no agronomic advantage under these stresses. To ensure successful seedling emergence and rapid turf canopy development, practitioners must prioritize optimal planting windows—such as spring or autumn for C₃ species and early-summer for C₄ species—and commit to frequent irrigation during the critical initial weeks of establishment.

Ultimately, the influence of irrigation frequency and proper planting timing far outweighed any benefits provided by the evaluated seed coatings. Turfgrass managers should not view current seed coatings as a substitute for standard, best management practices. Because this research was limited to specific coating materials and species, future studies are warranted to test additional coating formulations, seed treatments, and species across diverse stress conditions. Further evaluation of these technologies across varying soil types and deficit irrigation regimes will clarify whether specific coatings can offer measurable advantages under targeted environmental stresses.

References

- Association of Official Seed Analysts. Volume, 1. (2016). Principles and procedures, 2016. Association of Official Seed Analysts, Inc.
- Braun, R.C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022a). Review of cool-season turfgrass water use and requirements: I. Evapotranspiration and responses to deficit irrigation. *Crop Science*, 62, 1661–1684. <https://doi.org/10.1002/csc2.20791>
- Braun, R.C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022b). Review of cool-season turfgrass water use and requirements: II. Responses to drought stress. *Crop Science*, 62, 1685–1701. <https://doi.org/10.1002/csc2.20790>
- Braun, R. C., Mandal, P., Nwachukwu, E., & Stanton, A. (2024). The role of turfgrasses in environmental protection and their benefits to humans: Thirty years later. *Crop Science*, 64, 2909–2944. <https://doi.org/10.1002/csc2.21383>
- Braun, R. C., Patton, A. J., Braithwaite, E. T., & Kowalewski, A. R. (2020). Establishment of low-input turfgrass from seed with patch and repair mixtures: Mulch and starter fertilizer effects. *Crop Science*, 60, 3362–3376. <https://doi.org/10.1002/csc2.20266>
- Braun, R. C., Patton, A. J., Watkins, E., Hollman, A. B., Murphy, J. A., Park, B. S., Kowalewski, A. R., & Braithwaite, E. T. (2021). Optimal fine fescue mixture seeding dates in the northern United States. *Agronomy Journal*, 113, 4413–4428. <https://doi.org/10.1002/agj2.20859>
- Christians, N. E., Patton, A. J., & Law, Q. D. (2017). *Fundamentals of turfgrass management*. John Wiley & Sons.
- Colmer, T. D., & Barton, L. (2017). A review of warm-season turfgrass evapotranspiration, responses to deficit irrigation, and drought resistance. *Crop Science*, 57, S98–S110. <https://doi.org/10.2135/cropsci2016.10.0911>
- Fry, J., & Huang, B. (2004). *Applied Turfgrass Science and Physiology*. John Wiley & Sons.
- Gaussoin, R. E., & Branham B. E. (1989). Influence of cultural factors on species dominance in a mixed stand of annual bluegrass/creeping bentgrass. *Crop Science*, 29, 480–484. <https://doi.org/10.2135/cropsci1989.0011183X002900020048x>
- Ghali, I. E., Grabow, G. L., Huffman, R. L., & Miller, G. L. (2011). Comparing digital image analysis and other turf quality measurements in the evaluation of smart irrigation technologies, Doctoral dissertation, *North Carolina State University*.
- Halmer, P. (2008). Seed Technology and Seed Enhancement. *Acta Horticulturae*, 771, 17–26. <https://doi.org/10.17660/ActaHortic.2008.771.1>

- Hathcock, A. L., Dernoeden, P. H., Murray, J. J., & Wehner, D. J. (1984a). Seed germination of tall fescue and Kentucky bluegrass as affected by adhesives. *HortScience*, 19, 442–443. <https://doi.org/10.21273/HORTSCI.19.3.442>
- Hathcock, A. L., Dernoeden, P. H., Turner, T. R., & McIntosh, M. S. (1984b). Tall fescue and Kentucky bluegrass response to fertilizer and lime seed coatings. *Agronomy Journal*, 76, 879–883. <https://doi.org/10.2134/agronj1984.00021962007600060005x>
- Huang, B. (2008). Turfgrass water requirements and factors affecting water usage. *Water Quality and Quantity Issues for Turfgrass in Urban Landscapes. CAST Spec. Publ.*, 27, 193–205.
- Layton, J., Munshaw, G., Stewart, B., Baldwin, B., & Philley, H. (2007). Does seed coating affect bermudagrass germination? *ASA-CSSA-SSSA Annual Meeting Abstracts*. ASA, CSSA, and SSSA, Madison, WI.
- Leinauer, B., Serena, M., & Singh, D. (2010). Seed coating and seeding rate effects on turfgrass germination and establishment. *HortTechnology*, 20, 179–185. doi.org/10.21273/HORTTECH.20.1.179
- Madsen, M. D., Fidanza, M. A., Barney, N. S., Kostka, S. J., Badrakh, T., & McMillan, M. F. (2016). Low-dose application of nonionic alkyl terminated block copolymer surfactant enhances turfgrass seed germination and plant growth. *HortTechnology*, 26, 379–385. doi.org/10.21273/HORTTECH.26.4.379
- Madsen, M. D., Kostka, S. J., Hulet, A., Mackey, B. E., Harrison, M. A., & McMillan, M. F. (2013). Surfactant seed coating—a strategy to improve turfgrass establishment on water repellent soils. In *International Symposium on Adjuvants for Agrochemicals*, 205–210.
- Madsen, M. D., Petersen, S. L., & Taylor, A. G. (2017). Seed coating compositions and methods for applying soil surfactants to water-repellent soil. *U.S. Patent No. 9,554,502*. Washington, DC: U.S. Patent and Trademark Office.
- Madsen, M. D., Zvirzdin, D. L., Roundy, B. A., & Kostka, S. J. (2014). Improving reseeding success after catastrophic wildfire with surfactant seed coating technology. *Pesticide Formulation and Delivery Systems*, 33, 44–48.
- McMillan, M., Daroub, S., Moore, K., Erickson, J., Kostka, S., & Fidanza, M. (2023). Surfactant-coated seed emergence and establishment under deficit irrigation in hydrophilic and hydrophobic soils. *Journal of Environmental Horticulture*, 41, 33–39. <https://doi.org/10.24266/2573-5586-41.1.33>
- Moran, J., Goggi, A. S., Moore, K. J., Fei, S. Z., & Gruss, S. (2025). Improving groundcover 597 establishment through seed rate, seed ratio, and hydrophilic seed coating. *Agronomy*, 15, 598–1927. <https://doi.org/10.3390/agronomy15081927>
- Munshaw, G. C., Layton, J. M., Stewart, B. R., Philley, H. W., Beasley, J. S., & Lemus, R. W. (2014). The Germination responses of five bermudagrass cultivars to seed coating and temperature. *HortScience*, 49, 1225–1229. <https://doi.org/10.21273/HORTSCI.49.9.1225>

- Newell, A. J. (1997). Effect of different seed treatments and coatings on the germination and establishment of four grass species. *Journal of Turfgrass Science*, 73, 67–72.
- Newell, A. J., Hart-Woods, J. C., & Crossley, F. M. (1999). Investigation of the effects of Fortiva seed treatment on the establishment of different grass species and mixtures. *Journal of Turfgrass Science*, 75, 89–99.
- Paravar, A., Piri, R., Balouchi, H., & Ma, Y. (2023). Microbial seed coating: An attractive tool for sustainable agriculture. *Biotechnology Reports*, 37, e00781. <https://doi.org/10.1016/j.btre.2023.e00781>
- Patton, A. J., Hardebeck, G. A., Williams, D. W., & Reicher, Z. J. (2004). Establishment of bermudagrass and zoysiagrass by seed. *Crop Science*, 44, 2160–2167. <https://doi.org/10.2135/cropsci2004.2160>
- Reicher, Z. J., Throssell, C. S., & Weisenberger, D. V. (2000). Date of seeding affects establishment of cool-season turfgrasses. *HortScience*, 35, 1166–1169. <https://doi.org/10.21273/HORTSCI.35.6.1166>
- Richardson, M. D., & Hignight, K. W. (2010). Seedling emergence of tall fescue and Kentucky bluegrass, as affected by two seed coating techniques. *HortTechnology*, 20, 415–417. <https://doi.org/10.21273/HORTTECH.20.2.415>
- Richardson, M. D., Karcher, D. E., & Purcell, L. C. (2001). Quantifying turfgrass cover using digital image analysis. *Crop Science*, 41, 1884–1888. <https://doi.org/10.2135/cropsci2001.1884>
- Rocha, I., Ma, Y., Souza-Alonso, P., Vosátka, M., Freitas, H., & Oliveira, R. S. (2019). Seed coating: a tool for delivering beneficial microbes to agricultural crops. *Frontiers in Plant Science*, 10, 1357. <https://doi.org/10.3389/fpls.2019.01357>
- Serena, M., Leinauer, B., Sallenave, R., Schiavon, M., & Maier, B. (2012a). Media selection and seed coating influence germination of turfgrasses under salinity. *HortScience*, 47, 116–120. <https://doi.org/10.21273/HORTSCI.47.1.116>
- Serena, M., Leinauer, B., Sallenave, R., Schiavon, M., & Maier, B. (2012b). Turfgrass establishment from polymer-coated seed under saline irrigation. *HortScience*, 47, 1789–1794. <https://doi.org/10.21273/HORTSCI.47.12.1789>
- Serena, M., Leinauer, B., Velasco-Cruz, C., & Sevostianova, E. (2022). Optimizing frequency and amount of irrigation needed to establish cool-season turfgrasses. *Agronomy Journal*, 114, 1851–1858. <https://doi.org/10.1002/agj2.21046>
- Severmutlu, S., Mutlu, N., Shearman, R. C., Gurbuz, E., Gulsen, O., Hocagil, M., Karaguzel, O., Heng-Moss, T., Riordan, T. P., & Gaussoin, R. E. (2011). Establishment and turf qualities of warm-season turfgrasses in the Mediterranean region. *HortTechnology*, 21, 67–81. <https://doi.org/10.21273/HORTTECH.21.1.67>

- Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, 52, 591–611. <https://doi.org/10.1093/biomet/52.3-4.591>
- Sochorec, M., & Knot, P. (2013). The effect of fertilizer seed coating on the germinating capacity and initial development of some turf grass species and white clover. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 60, 23.
- Sun, T., Wang, W., & Chan, Z. (2024). How do cool-season turfgrasses respond to high temperature: progress and challenges. *Grass Research*, 4. <https://doi.org/10.48130/grares-0024-0008>
- Svejcar, L. N., Brown, V. S., Ritchie, A. L., Davies, K. W., & Svejcar, T. J. (2022). A new perspective and approach to ecosystem restoration: a seed enhancement technology guide and case study. *Restoration Ecology*, 30. <https://doi.org/10.1111/rec.13615>
- United States Department of Agriculture, Natural Resources Conservation Service. (USDA-NRCS). (2011). *Calculating Seeding Rates for Conservation Plantings* (Plant Materials Technical Note No: TX-PM-12-02).
- Wynne, T., & Devitt, D. (2020). Evapotranspiration of urban landscape trees and turfgrass in an arid environment: potential trade-offs in the landscape. *HortScience*, 55, 1558–1566. <https://doi.org/10.21273/HORTSCI15027-20>

Chapter 6 - Summary

Driven by promises of improved handling, storage longevity, establishment, and stress tolerance, the global seed coating market is projected to reach \$3.5 billion by 2030. Although seed coating technology has evolved from simple physical binders into functional delivery systems for nutrients, moisture-absorbents, and pesticides, independent research validating its actual effectiveness in turfgrass establishment and storage remains severely limited. The literature review (Chapter 1) showed that previous studies of turfgrass seed coatings have reported mixed results, with coating effects being inconsistent and dependent on the formulation (i.e., coating), species, and environment. The overall goal of this dissertation was to evaluate the effects of turfgrass seed coating, especially a limestone-based superabsorbent seed coating, on short- and long-term seed storage, germination, seedling vigor, and establishment.

The effects of seed coating on turfgrass storage and longevity remain unclear, prompting Chapters 2 and 3 to test coated versus noncoated seed under different storage conditions and durations. Synthesizing the controlled short-term thermal stress trials of Chapter 2 with the multi-year storage evaluations of Chapter 3 reveals a definitive principle of seed preservation: ambient environmental stability overwhelmingly supersedes physical coating technology. This research established a clear physiological threshold at approximately 42 °C, above which seed moisture content drops rapidly and seed viability deteriorates, regardless of whether the seed is coated or raw (i.e., noncoated). While limestone coatings occasionally offered minor, species-specific improvements in initial germination speed under baseline conditions, they provided zero buffering capacity against acute high-temperature spikes above 42 °C or the compounding, high-humidity deterioration experienced in non-insulated (i.e., non-climate-controlled) shed storage over a two-year period. Because the forced-air drying used during the manufacturing process

leaves coated seed with a lower initial moisture content than noncoated seed, turfgrass practitioners cannot rely on these materials as an artificial shield against suboptimal warehousing. Ultimately, maintaining cool, climate-controlled storage remains the essential requirement for preserving turfgrass seed vigor.

Shifting from storage to establishment, Chapters 4 and 5 evaluated the establishment of coated versus noncoated seed under greenhouse and field conditions. Across both environments, the results demonstrated that seed coatings cannot substitute for fundamental soil moisture management during turfgrass establishment. While superabsorbent coatings are often marketed to reduce water requirements, their actual effects in these trials were minor and inconsistent. Instead, establishment success was dictated entirely by soil water-holding capacity, irrigation frequency, and planting season. In the field, severe summer heat and rapid soil drying caused widespread establishment failure across all species, proving that limestone coatings offer no meaningful protection against acute drought stress. Furthermore, while frequent irrigation drove faster initial turfgrass cover, this advantage naturally faded once functional root systems developed. Ultimately, turfgrass managers must focus on maintaining adequate soil moisture during the critical first few weeks of seeding, rather than relying on seed coatings to compensate for deficit irrigation, poor soil water-holding capacity (i.e., sandy soils), or poorly timed planting.

While these findings should not be generalized to all seed coating technologies, the takeaway for limestone-based formulations is definitive: they act primarily as inert fillers and provide no substantial agronomic benefit. Consequently, seed distributors, warehousing operations, and turfgrass practitioners must respect the physiological thermal ceiling identified in this research, avoiding ambient storage temperatures above 42 °C. Beyond this threshold, seed moisture declines rapidly and viability deteriorates. Distributors cannot rely on physical seed

coatings to buffer against extreme heat spikes or the compounding, high-humidity deterioration typical of non-insulated storage sheds. Furthermore, because the forced-air drying utilized during manufacturing actually leaves coated seed with a lower initial moisture content than noncoated seed, coated products might enter the supply chain at an immediate physiological disadvantage. Therefore, prioritizing cool, climate-controlled, and environmentally stable storage remains an essential biological prerequisite for preserving turfgrass seed quality.

For turfgrass superintendents, managers, and consumers, these results present a critical economic finding. Because coated and noncoated seeds demonstrated overwhelmingly similar performance across these trials, purchasing limestone-coated seed means paying a higher price for substantially fewer pure live seeds (PLS) per unit of weight. Buyers should evaluate seed bids strictly on a PLS basis rather than gross bag weight. In the field, practitioners cannot rely on limestone-based superabsorbent coatings to reduce water requirements or extend irrigation intervals during seeding. Successful establishment is governed entirely by the availability of soil moisture, soil texture, and irrigation frequency during the critical first few weeks post-seeding. Once a functional root system develops, managers and homeowners can safely transition to lower irrigation amounts or wider watering intervals to maintain turf cover.

Finally, these results challenge the seed industry to move beyond basic limestone fillers. Because limestone provides no measurable protection against heat or drought stress, formulations must transition beyond simple physical coverings. To justify higher consumer prices, the industry needs to develop more functional coatings. Future research should focus on proving that active ingredients—like genuine water-absorbents, growth regulators, or targeted nutrients—actually improve the seed's environment and deliver reliable benefits in both storage and the field.

Appendix A - Additional Figures and Tables for Chapter 2

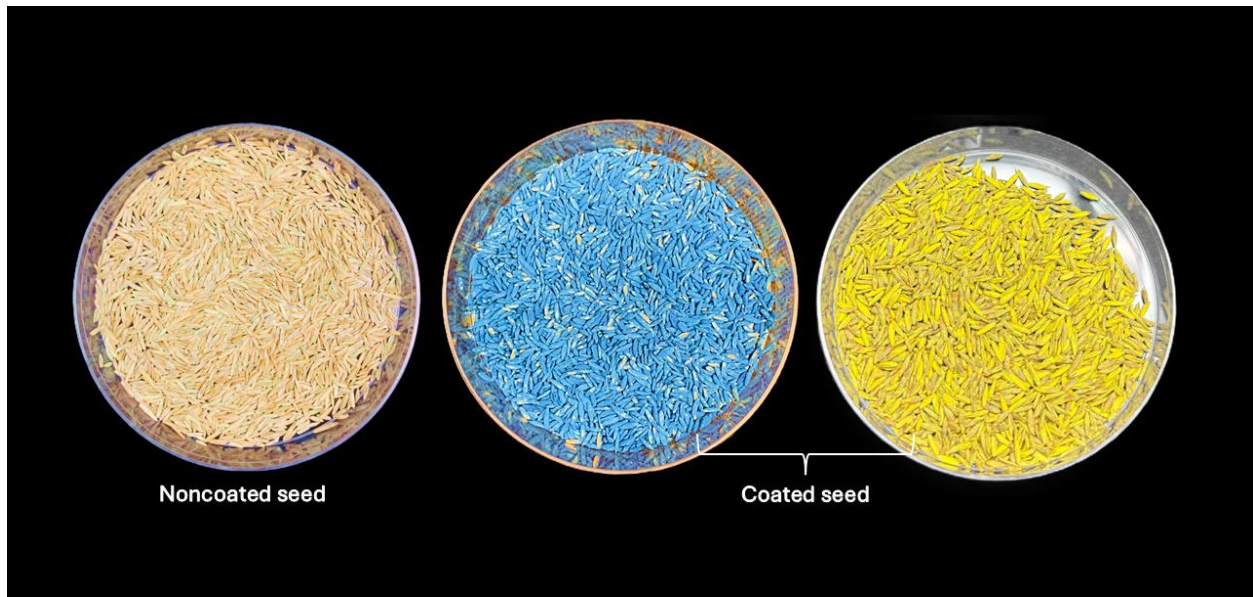


Figure A.1. Noncoated and coated turfgrass seed samples used in the short-term storage experiments. Noncoated seed is shown on the left, while coated seed samples are shown in the middle and right Petri dishes.

Table A.1. Effect of seed coating and storage temperature on germination speed (DG50 and MGT) of multiple cool-season turfgrass species in Experiment 1.

Species	Tall fescue		Kentucky bluegrass		Strong creeping red fescue		Perennial ryegrass	
	DG ₅₀	MGT	DG ₅₀	MGT	DG ₅₀	MGT	DG ₅₀	MGT
days								
Seed coating								
Noncoated	7.4 a	8.3 a	10.7 a	11.6 a	8.1 a	9.1 a	5.2 b	5.2 b
Coated	7.0 b	7.8 b	10.0 b	10.8 b	7.1 b	7.9 b	6.2 a	6.2 a
Storage temperature								
4 °C	7.2	8.1	9.7 c	10.6 c	7.3 c	8.2 b	5.7 b	5.7 b
22 °C	7.1	8.0	9.6 c	10.5 c	7.5 bc	8.4 ba	5.4 b	5.4 b
42 °C	7.0	7.8	10.8 b	11.5 b	7.8 ba	8.7 a	5.5 b	5.5 b
62 °C	7.4	8.2	11.2 a	12.0 a	7.9 a	8.7 a	6.2 a	6.2 a
<i>p</i> values								
Seed coating	0.0027	0.0005	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Storage temperature	0.2437	0.2130	<.0001	<.0001	0.0011	0.0079	0.0001	0.0001
Seed coating × Storage temperature	0.6182	0.5189	0.0269	0.0057	0.5212	0.3297	0.0132	0.0132

Note: Means within a column followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Abbreviations: DG₅₀ (days), days to 50% germination extracted from four-parameter sigmoidal regression model; MGT (days), Mean Germination Time.

Appendix B - Additional Figures and Tables for Chapter 3



Figure B.1. Seed sample preparation and weighing for seed moisture content determination. (A) Labeled seed envelopes organized prior to weighing. (B) Coated turfgrass seed weighed using an analytical balance before seed moisture content analysis.



Figure B.2. Germination testing and data collection procedure for turfgrass seed. (A) Petri dishes placed inside the growth chamber for germination (B) Germinated seeds identified based on visible radicle and plumule emergence. (C) Close-up view of germinated seeds on blotter paper. (D) Daily germination counting procedure, in which germinated seeds were counted, removed, and the Petri dishes were placed back to the growth chamber for continued evaluation over 28 days.

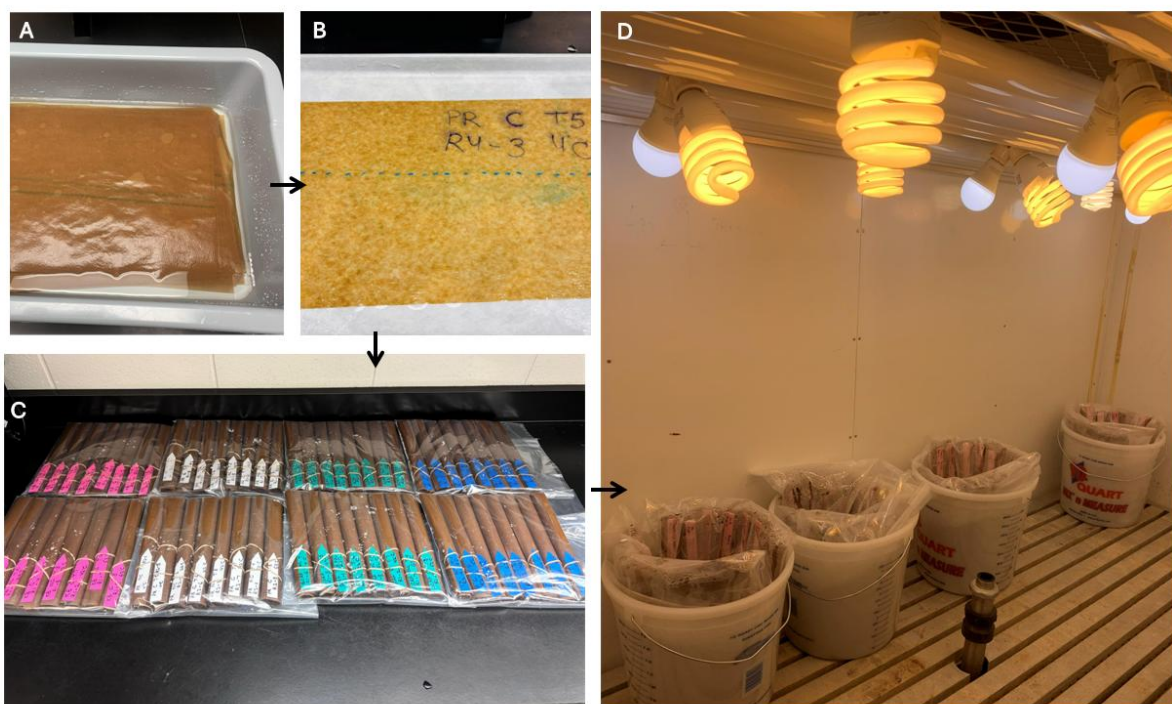


Figure B.3. Paper towel method for seedling vigor evaluation of turfgrass seed. (A) Germination paper moistened before seed placement. (B) Seeds placed on labeled germination paper according to treatment and replication. (C) Prepared rolled towels enclosed in plastic bags to maintain moisture during incubation. (D) Rolled towel samples placed upright in containers inside the growth chamber for seedling development.



Figure B.4. Seedling vigor measurements of turfgrass seed after 21 days of incubation in a growth chamber. (A) Germinated seedlings arranged on moist germination paper before measurement. (B) Root and shoot lengths measured using a digital vernier caliper to quantify seedling growth.

Table B.1. Effects of coating, storage condition, and their interaction on seed moisture content (%) of cool-season turfgrass species across years in Run 1

	Seed moisture content (%)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	3.8 b	4.7 b	3.7 b	4.5 b	4.7 b	3.7 b	4.1 b	4.1 b	3.0 b	2.1 b	2.5 b	1.8 b
Noncoated	7.0 a	9.1 a	7.1 a	8.6 a	8.9 a	7.1 a	8.1 a	8.7 a	6.4 a	7.3 a	8.8 a	6.6 a
Storage condition												
Indoor	5.4	6.3 b	5.2 c	6.5	6.1 b	5.1 c	6.1	5.9 b	4.5 c	4.7	5.2 b	4.0 b
Refrigerator	–	6.2 b	5.3 b	–	5.9 c	5.4 b	–	5.7 c	4.7 b	–	5.0 b	4.3 a
Shed	–	8.2 a	5.8 a	–	8.3 a	5.6 a	–	7.7 a	4.9 a	–	6.8 a	4.3 a
Coating × Storage condition												
Coated × Indoor	–	4.2 e	3.6 e	–	4.2 e	3.5 d	–	3.8 e	2.9 d	–	2.3 e	1.8 d
Coated × Refrigerator	–	4.3 e	3.7 e	–	4.0 e	3.7 d	–	3.7 e	3.0 d	–	2.3 e	1.9 d
Coated × Shed	–	5.5 d	3.9 d	–	5.8 d	3.8 d	–	4.9 d	3.0 d	–	3.0 d	1.8 d
Noncoated × Indoor	–	8.4 b	6.7 c	–	8.1 b	6.7 c	–	8.0 b	6.1 c	–	8.0 b	6.3 c
Noncoated × Refrigerator	–	8.1 c	6.8 b	–	7.8 c	7.1 b	–	7.7 c	6.3 b	–	7.8 c	6.6 b
Noncoated × Shed	–	10.8 a	7.7 a	–	10.7 a	7.5 a	–	10.4 a	6.7 a	–	10.6 a	6.8 a
<i>p</i> values												
Coating	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0002	<.0001	<.0001	0.0001	<.0001	<.0001
Storage condition	–	<.0001	<.0001	–	<.0001	<.0001	–	<.0001	0.0001	–	<.0001	<.0001
Coating × Storage condition	–	<.0001	<.0001	–	<.0001	0.0038	–	<.0001	0.004	–	<.0001	0.0003

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline seed moisture content prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.2. Effects of coating, storage condition, and their interaction on seed moisture content (%) of cool-season turfgrass species across years in Run 2.

	Seed moisture content (%)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	3.8 b	4.4 b	4.7 b	4.7 b	4.3 b	4.7 b	4.2 b	3.9 b	4.0 b	2.1 b	2.3 b	2.6 b
Noncoated	7.0 a	8.5 a	8.8 a	8.5 a	8.3 a	8.7 a	8.1 a	8.0 a	8.3 a	7.3 a	7.9 a	8.8 a
Storage condition												
Indoor	5.4	6.4 b	6.8 b	6.6	6.4 b	6.7 b	6.2	6.0 b	6.0 b	4.7	5.2 b	5.7 b
Refrigerator	–	6.0 c	5.2 c	–	5.9 c	5.4 c	–	5.6 c	5.1 c	–	4.8 c	4.8 c
Shed	–	6.8 a	8.2 a	–	6.6 a	8.1 a	–	6.3 a	7.2 a	–	5.4 a	6.7 a
Coating × Storage condition												
Coated × Indoor	–	4.4 e	4.7 e	–	4.3 d	4.7 e	–	3.9 ed	3.9 e	–	2.3 ed	2.6 e
Coated × Refrigerator	–	4.1 f	3.7 f	–	4.0 e	3.8 f	–	3.8 e	3.3 f	–	2.2 e	2.2 f
Coated × Shed	–	4.6 d	5.6 d	–	4.5 d	5.6 d	–	4.1 d	4.7 d	–	2.4 d	3.1 d
Noncoated × Indoor	–	8.5 b	8.8 b	–	8.4 b	8.7 b	–	8.0 b	8.1 b	–	7.9 b	8.8 b
Noncoated × Refrigerator	–	7.9 c	6.7 c	–	7.8 c	6.9 c	–	7.4 c	6.9 c	–	7.3 c	7.3 c
Noncoated × Shed	–	9.0 a	10.8 a	–	8.8 a	10.6 a	–	8.5 a	9.7 a	–	8.5 a	10.3 a
<i>p</i> values												
Coating	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0002	<.0001	<.0001	0.0001	<.0001	<.0001
Storage condition	–	<.0001	<.0001	–	<.0001	<.0001	–	<.0001	<.0001	–	<.0001	<.0001
Coating × Storage condition	–	<.0001	<.0001	–	0.0007	<.0001	–	0.0002	<.0001	–	<.0001	<.0001

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline seed moisture content prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.3. Effects of coating, storage condition, and their interaction on germination (%) of cool-season turfgrass species across years in Run 1.

	Germination (%)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	96.9	93.2 a	87.5 a	93.7 a	89.9 a	69.7 a	85.4 a	69.6	50.1	84.1	78.9 b	65.4
Noncoated	91.2	88.5 b	82.9 a	80.6 b	80.5 b	53.4 b	80.1 b	66.9	47.2	83.8	84.8 a	66.4
Storage condition												
Indoor	94.1	92.2	90.5 a	87.2	90.8 a	80.4 b	82.7	79.9 a	67.7 b	83.9	84.9 a	78.3 b
Refrigerator	–	90.6	92.2 a	–	88.9 a	88.8 a	–	82.5 a	76.7 a	–	84.4 a	85.4 a
Shed	–	89.7	72.9 b	–	75.8 b	15.5 c	–	42.4 b	1.6 c	–	76.3 b	34.1 c
Coating × Storage condition												
Coated × Indoor	–	93.9	94.6	–	92.6 a	91.2	–	82.6	67.2	–	82.3 b	74.5 b
Coated × Refrigerator	–	91.9	94.7	–	92.0 a	94.5	–	83.1	81.9	–	79.7 cb	82.1 ba
Coated × Shed	–	93.7	73.3	–	85.2 a	23.6	–	43.2	1.4	–	74.7 d	39.6 c
Noncoated × Indoor	–	90.5	86.4	–	89.1 a	69.6	–	77.2	68.3	–	87.5 a	82.0 ba
Noncoated × Refrigerator	–	89.2	89.7	–	85.8 a	83.2	–	81.9	71.5	–	89.1 a	88.7 a
Noncoated × Shed	–	85.8	72.6	–	66.5 b	7.4	–	41.7	1.8	–	78.0 cd	28.6 d
<i>p</i> values												
Coating	0.0815	0.0008	0.0048	0.0004	0.0004	<.0001	0.0466	0.1418	0.2702	0.9106	<.0001	0.698
Storage condition	–	0.2251	<.0001	–	<.0001	<.0001	–	<.0001	<.0001	–	<.0001	<.0001
Coating × Storage condition	–	0.1609	0.1256	–	0.0224	0.1869	–	0.5714	0.1521	–	0.0454	0.0168

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline germination (%) prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.4. Effects of coating, storage condition, and their interaction on germination (%) of cool-season turfgrass species across years in Run 2.

	Germination (%)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	96.5 a	94.1 a	93.8 a	93.4 a	94.3 a	76.2 b	85.4 a	82.1 a	55.6 a	86.6	85.6 b	82.4
Noncoated	91.4 b	89.5 b	86.5 b	82.9 b	86.4 b	82.9 a	80.1 b	76.5 b	50.1 b	87.1	90.1 a	82.8
Storage condition												
Indoor	93.9	91.9 ba	92.3 a	88.1	91.1 a	79.8 b	82.7	81.7 a	63.3 a	86.9	86.5	83.8 b
Refrigerator	–	93.4 a	90.9 a	–	91.7 a	92.0 a	–	80.7 a	67.6 a	–	89.5	87.7 a
Shed	–	90.1 b	87.3 b	–	88.4 b	66.8 b	–	75.6 b	27.5 b	–	87.6	76.3 c
Coating × Storage condition												
Coated × Indoor	–	95.0	95.6	–	94.5 a	72.3 c	–	83.0	64.9	–	85.8 c	81.4 b
Coated × Refrigerator	–	96.2	94.9	–	94.1 a	94.5 a	–	85.3	74.5	–	85.6 c	86.4 a
Coated × Shed	–	91.2	90.8	–	94.3 a	61.8 d	–	78.2	27.3	–	85.5 c	79.3 b
Noncoated × Indoor	–	88.8	88.9	–	87.7 b	87.3 b	–	80.5	61.7	–	87.2 cb	86.2 a
Noncoated × Refrigerator	–	90.6	86.9	–	89.2 b	89.6 ba	–	76.2	60.8	–	93.5 a	88.9 a
Noncoated × Shed	–	89.0	83.8	–	82.5 c	71.9 ba	–	72.9	27.8	–	89.6 b	73.4 c
<i>p</i> values												
Coating	0.0065	<.0001	<.0001	0.0312	<.0001	0.0205	0.0466	0.0011	0.0415	0.8711	0.0003	0.7169
Storage condition	–	0.0073	0.0023	–	0.0334	<.0001	–	0.0054	<.0001	–	0.0611	<.0001
Coating × Storage condition	–	0.0815	0.8316	–	0.0316	0.0178	–	0.1838	0.0796	–	0.0445	0.0113

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline germination (%) prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.5. Effects of coating, storage condition, and their interaction on mean germination time (days) of cool-season turfgrass species across years in Run 1.

	Mean Germination Time (days)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	5.7 b	6.2 b	7.3 b	10.8 b	9.0 b	11.0 b	7.6 a	9.1 a	8.7	10.8 b	10.2 a	11.3
Noncoated	7.2 a	6.6 a	7.7 a	14.3 a	10.0 a	12.4 a	7.1 b	8.1 b	9.5	13.0 a	9.6 b	10.9
Storage condition												
Indoor	6.4	6.0 b	6.9 c	12.5	8.8 b	11.0 b	7.4	8.1 b	9.2	11.9	9.5 b	9.8 b
Refrigerator	–	6.7 a	7.2 b	–	9.2 b	10.1 b	–	8.2 b	9.0	–	9.5 b	9.3 b
Shed	–	6.6 a	8.3 a	–	10.6 a	14.0 a	–	9.5 a	9.2	–	10.8 a	14.2 a
Coating × Storage condition												
Coated × Indoor	–	5.9 c	6.7 dc	–	8.3	10.5	–	8.4 cb	9.5	–	9.6	9.4 dc
Coated × Refrigerator	–	6.2 cb	6.5 d	–	8.7	9.2	–	8.5 b	9.3	–	10.1	9.0 d
Coated × Shed	–	6.6 b	8.5 a	–	10.1	13.3	–	10.3 a	7.4	–	11.0	15.5 a
Noncoated × Indoor	–	6.0 c	7.0 c	–	9.3	11.4	–	7.9 c	9.0	–	9.3	10.1 c
Noncoated × Refrigerator	–	7.1 a	8.0 b	–	9.6	11.1	–	7.9 c	8.7	–	8.9	9.7 dc
Noncoated × Shed	–	6.6 b	8.1 ba	–	11.2	14.7	–	8.6 b	11.0	–	10.7	12.9 b
<i>p</i> values												
Coating	0.0038	0.0052	0.0027	0.0002	0.0008	0.0006	0.0274	<.0001	0.6070	0.0144	0.0089	0.0640
Storage condition	–	0.0001	<.0001	–	<.0001	<.0001	–	<.0001	0.9910	–	<.0001	<.0001
Coating × Storage condition	–	0.0078	<.0001	–	0.9678	0.5032	–	0.0081	0.4608	–	0.1448	<.0001

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline mean germination time (days) prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.6. Effects of coating, storage condition, and their interaction on mean germination time (days) of cool-season turfgrass species across years in Run 2.

	Mean Germination Time (days)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	5.9 b	5.5 b	7.1	10.6 b	8.8 b	10.8 b	7.6 a	8.7	11.0	10.8 b	10.1 a	11.0 a
Noncoated	7.2 a	5.9 a	7.4	13.5 a	10.7 a	11.8 a	7.1 b	8.4	11.0	12.5 a	9.5 b	9.9 b
Storage condition												
Indoor	6.6	5.7	7.0	12.1	9.7	11.0 b	7.4	8.2 b	10.1 b	11.6	9.6	10.2 b
Refrigerator	–	5.8	7.5	–	9.4	10.7 b	–	8.7 a	10.3 b	–	9.8	10.0 b
Shed	–	5.8	7.4	–	10.1	12.3 a	–	8.7 a	12.6 a	–	10.0	11.2 a
Coating × Storage condition												
Coated × Indoor	–	5.4	6.8	–	8.9	10.5 c	–	8.3	10.0	–	9.7	10.3 b
Coated × Refrigerator	–	5.6	7.2	–	8.7	9.6 d	–	9.0	10.1	–	10.3	10.5 b
Coated × Shed	–	5.6	7.3	–	8.7	12.4 a	–	8.8	12.9	–	10.3	12.2 a
Noncoated × Indoor	–	6.0	7.1	–	10.5	11.5 b	–	8.2	10.3	–	9.5	10.1 cb
Noncoated × Refrigerator	–	5.9	7.8	–	10.2	11.8 ba	–	8.5	10.4	–	9.4	9.4 c
Noncoated × Shed	–	5.9	7.4	–	11.4	12.2 ba	–	8.6	12.3	–	9.7	10.1 cb
<i>p</i> values												
Coating	0.0445	0.0007	0.0590	0.0036	<.0001	0.0009	0.0274	0.1472	0.9429	0.0187	0.0009	<.0001
Storage condition	–	0.7591	0.0603	–	0.1384	0.0002	–	0.035	<.0001	–	0.1277	0.0013
Coating × Storage condition	–	0.5146	0.3816	–	0.1307	0.0026	–	0.4946	0.3358	–	0.1472	0.0088

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline mean germination time (days) prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.7. Effects of coating, storage condition, and their interaction on days to 50% germination (DG₅₀) of cool-season turfgrass species across years in Run 1.

	DG ₅₀ (days)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	5.1 b	5.5 b	6.4 b	10.1 b	8.0 b	10.0 b	6.7 a	8.1 a	10.1 a	10.2 b	9.3 a	10.4
Noncoated	6.1 a	5.8 a	6.6 a	13.7 a	9.0 a	11.5 a	6.1 b	7.2 b	7.4 b	12.3 a	8.8 b	10.0
Storage condition												
Indoor	5.6	5.2 b	6.0 c	11.9	7.8 b	9.9 b	6.4	7.2 b	8.2 b	11.2	8.7 b	8.8 b
Refrigerator	–	5.8 a	6.3 b	–	8.2 b	9.0 c	–	7.4 b	8.0 b	–	8.7 b	8.5 b
Shed	–	5.8 a	7.3 a	–	9.4 a	13.4 a	–	8.4 a	10.1 a	–	9.9 a	13.4 a
Coating × Storage condition												
Coated × Indoor	–	5.1 c	5.9 c	–	7.4	9.4	–	7.5 cbd	8.4 b	–	8.8	8.6 dc
Coated × Refrigerator	–	5.4 c	5.9 c	–	7.7	8.3	–	7.7 b	8.4 b	–	9.2	8.1 d
Coated × Shed	–	5.8 b	7.6 a	–	8.8	12.3	–	9.2 a	13.5 a	–	10.1	14.8 a
Noncoated × Indoor	–	5.3 c	6.1 c	–	8.2	10.4	–	7.0 d	8.0 cb	–	8.6	9.1 c
Noncoated × Refrigerator	–	6.2 a	6.8 b	–	8.7	9.7	–	7.1 cd	7.5 cd	–	8.2	8.8 dc
Noncoated × Shed	–	5.8 b	7.0 b	–	10.0	14.5	–	7.6 cb	6.7 d	–	9.8	12.1 b
<i>p</i> values												
Coating	0.0091	0.0099	0.0431	0.0002	0.0008	0.0005	0.0142	<.0001	<.0001	0.0165	0.0103	0.0652
Storage condition	–	0.0002	<.0001	–	0.0002	<.0001	–	<.0001	0.0001	–	<.0001	<.0001
Coating × Storage condition	–	0.0138	<.0001	–	0.8744	0.32	–	0.0104	<.0001	–	0.1579	<.0001

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline DG₅₀ prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.8. Effects of coating, storage condition, and their interaction on days to 50% germination (DG₅₀) of cool-season turfgrass species across years in Run 2.

	DG ₅₀ (days)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	5.2	4.8 b	6.2	9.8 b	7.9 b	9.8 b	6.7 a	7.8	9.9	10.0 b	9.3 a	10.2 a
Noncoated	6.3	5.2 a	6.4	12.8 a	9.5 a	11.0 a	6.1 b	7.5	9.8	11.4 a	8.8 b	9.0 b
Storage condition												
Indoor	5.8	4.9	6.1	11.3	8.7	10.2 b	6.4	7.3 b	9.0 b	10.7	8.8	9.3 b
Refrigerator	–	4.9	6.4	–	8.4	9.7 b	–	7.8 a	8.9 b	–	9.0	9.0 b
Shed	–	5.0	6.5	–	9.0	11.3 a	–	7.8 a	11.6 a	–	9.2	10.4 a
Coating × Storage condition												
Coated × Indoor	–	4.7	6.0	–	8.1	9.6 b	–	7.4	8.9	–	9.0	9.5 b
Coated × Refrigerator	–	4.8	6.1	–	7.8	8.5 c	–	8.1	8.9	–	9.4	9.5 b
Coated × Shed	–	4.9	6.6	–	7.8	11.3 a	–	7.9	12.0	–	9.4	11.6 a
Noncoated × Indoor	–	5.0	6.1	–	9.3	10.8 a	–	7.3	9.1	–	8.7	9.2 b
Noncoated × Refrigerator	–	5.0	6.7	–	9.1	10.8 a	–	7.6	9.0	–	8.7	8.5 c
Noncoated × Shed	–	5.1	6.5	–	10.1	11.3 a	–	7.7	11.3	–	8.9	9.2 b
<i>p</i> values												
Coating	0.0659	0.0066	0.1580	0.0041	<.0001	0.0003	0.0142	0.0509	0.6545	0.0213	0.0010	<.0001
Storage condition	–	0.5005	0.0629	–	0.2049	0.0003	–	0.0169	<.0001	–	0.0859	<.0001
Coating × Storage condition	–	0.8515	0.201	–	0.1293	0.0055	–	0.4565	0.2363	–	0.3703	0.0007

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline DG₅₀ prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.9. Effects of coating, storage condition, and their interaction on shoot length (mm) of cool-season turfgrass species across years in Run 1.

	Shoot length (mm)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	54.4	61.9	62.0 a	61.7	74.0 a	63.9	43.2	50.2	52.0 a	26.7	33.0	30.2
Noncoated	51.6	57.9	57.9 b	52.7	67.1 b	63.2	43.7	48.0	48.4 b	27.0	32.8	32.8
Storage condition												
Indoor	53.0	61.3	57.6	57.2	68.4	67.0 a	43.47	49.5	50.7	26.9	34.4	32.5 a
Refrigerator	–	58.6	61.7	–	72.2	66.1 a	–	49.8	49.7	–	33.1	33.0 a
Shed	–	59.8	60.6	–	71.0	57.7 b	–	48.0	–	–	31.4	29.1 b
Coating × Storage condition												
Coated × Indoor	–	64.0	58.9	–	72.3	72.5 a	–	49.9	52.8	–	35.3 a	31.6
Coated × Refrigerator	–	59.6	65.2	–	74.3	65.2 a	–	53.0	51.1	–	30.7 b	31.4
Coated × Shed	–	62.2	61.8	–	75.3	54.1 b	–	47.8	–	–	33.0 ba	27.6
Noncoated × Indoor	–	58.5	56.2	–	64.5	61.5 ba	–	49.1	48.5	–	33.4 ba	33.4
Noncoated × Refrigerator	–	57.6	58.1	–	70.1	66.9 a	–	46.7	48.3	–	35.4 a	34.5
Noncoated × Shed	–	57.5	59.3	–	66.7	61.3 ba	–	48.2	–	–	29.7 b	30.5
<i>p</i> values												
Coating	0.4330	0.0711	0.0162	0.1005	0.0044	0.7994	0.8962	0.2398	0.0064	0.9233	0.8616	0.0502
Storage condition	–	0.5958	0.1057	–	0.3304	0.0390	–	0.6855	0.3550	–	0.0879	0.0416
Coating × Storage condition	–	0.7911	0.3978	–	0.6618	0.0421	–	0.3093	0.4876	–	0.0128	0.8973

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline shoot length (mm) prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.10. Effects of coating, storage condition, and their interaction on shoot length (mm) of cool-season turfgrass species across years in Run 2.

	Shoot length (mm)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	51.3	58.0	57.0 a	59.8	70.0 a	71.2 a	44.1	50.0	48.9	28.8	32.3	29.3
Noncoated	54.6	53.7	54.3 b	54.1	66.8 b	58.9 b	47.1	49.0	47.9	27.8	32.3	28.1
Storage condition												
Indoor	52.9	54.2	57.0 a	56.9	66.8	60.7 b	45.6	50.6	49.3 a	28.3	31.3	29.6 a
Refrigerator	–	55.4	58.9 a	–	68.0	72.3 a	–	48.3	49.6 a	–	33.2	30.2 a
Shed	–	58.0	51.1 b	–	70.4	62.2 b	–	49.6	46.2 b	–	32.3	26.2 b
Coating × Storage condition												
Coated × Indoor	–	56.1	58.6	–	73.9 a	67.3	–	50.5	53.5 a	–	32.3	29.9
Coated × Refrigerator	–	57.0	59.6	–	65.5 b	77.9	–	48.8	50.1 ba	–	33.0	31.1
Coated × Shed	–	60.9	52.9	–	70.5 ba	68.3	–	50.9	43.1 d	–	31.6	26.9
Noncoated × Indoor	–	52.2	55.4	–	59.6 c	54.0	–	50.7	45.2 dc	–	30.4	29.2
Noncoated × Refrigerator	–	53.8	58.2	–	70.4 ba	66.7	–	47.8	49.1 bc	–	33.3	29.4
Noncoated × Shed	–	55.2	49.4	–	70.3 ba	56.2	–	48.4	49.3 b	–	33.0	25.5
<i>p</i> values												
Coating	0.2446	0.0520	0.0181	0.2251	0.0352	<.0001	0.1469	0.5817	0.3583	0.5224	0.9629	0.2226
Storage condition	–	0.3085	<.0001	–	0.1244	0.0011	–	0.6051	0.0445	–	0.3563	0.0110
Coating × Storage condition	–	0.8709	0.6471	–	0.0001	0.9226	–	0.8374	0.0003	–	0.4274	0.8973

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline shoot length (mm) prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.11. Effects of coating, storage condition, and their interaction on root length (mm) of cool-season turfgrass species across years in Run 1.

	Root length (mm)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	56.1	62.2	59.5 a	61.4	53.9 a	48.7	37.0	40.0	31.9	18.3	19.5	16.2 b
Noncoated	52.1	59.6	53.3 b	51.7	44.4 b	44.6	33.9	38.6	31.1	18.5	20.0	20.9 a
Storage condition												
Indoor	54.1	65.2 a	55.0	56.6	47.0 b	45.9	35.5	40.4	29.5 b	18.4	20.9	18.7
Refrigerator	–	57.8 b	58.9	–	52.1 a	49.7	–	39.2	33.5 a	–	19.3	19.7
Shed	–	59.6 b	55.2	–	48.5 ba	44.4	–	38.3	–	–	19.1	17.1
Coating × Storage condition												
Coated × Indoor	–	66.6	56.4	–	51.9	49.1	–	40.5	30.7	–	19.4	17.2
Coated × Refrigerator	–	60.8	64.8	–	55.7	53.2	–	40.9	33.2	–	20.6	16.6
Coated × Shed	–	59.4	57.2	–	54.2	43.8	–	38.6	–	–	18.4	14.8
Noncoated × Indoor	–	63.9	53.7	–	42.2	42.7	–	40.3	28.3	–	22.3	20.3
Noncoated × Refrigerator	–	54.9	53.0	–	48.4	46.1	–	37.5	33.8	–	18.0	22.9
Noncoated × Shed	–	59.9	53.3	–	42.7	44.9	–	38.1	–	–	19.8	19.5
<i>p</i> values												
Coating	0.4196	0.0983	0.0144	0.0920	<.0001	0.0928	0.4381	0.4880	0.5595	0.9093	0.5965	0.0007
Storage condition	–	0.0031	0.3083	–	0.0468	0.1838	–	0.6857	0.0204	–	0.3187	0.1820
Coating × Storage condition	–	0.2491	0.2300	–	0.5554	0.3448	–	0.775	0.3393	–	0.1106	0.5331

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline root length (mm) prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.12. Effects of coating, storage condition, and their interaction on root length (mm) of cool-season turfgrass species across years in Run 2.

	Root length (mm)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	62.6 a	63.6	56.6	52.2	52.0 a	55.0 a	35.6	34.7	32.9	18.9	18.9 b	19.3 b
Noncoated	55.2 b	62.9	57.2	47.9	46.8 b	44.6 b	38.9	31.3	31.9	17.8	22.7 a	23.4 a
Storage condition												
Indoor	58.9	62.1	58.3	50.1	48.5	48.1	37.3	34.5	33.4	18.3	21.6 a	20.8
Refrigerator	–	63.0	58.0	–	51.1	53.5	–	33.3	33.7	–	22.0 a	22.4
Shed	–	64.5	54.4	–	48.7	47.9	–	31.2	30.2	–	18.8 b	20.9
Coating × Storage condition												
Coated × Indoor	–	64.5	57.5	–	53.9	54.2	–	34.4	34.8	–	20.0	19.1
Coated × Refrigerator	–	63.7	58.3	–	50.8	55.1	–	33.8	34.0	–	20.5	20.6
Coated × Shed	–	62.6	54.2	–	51.3	55.8	–	35.8	29.9	–	16.3	18.2
Noncoated × Indoor	–	59.8	59.2	–	43.1	42.0	–	34.5	32.0	–	23.3	22.5
Noncoated × Refrigerator	–	62.4	57.8	–	51.3	51.8	–	32.8	33.4	–	23.5	24.3
Noncoated × Shed	–	66.5	54.6	–	46.1	40.1	–	26.6	30.5	–	21.5	23.5
<i>p</i> values												
Coating	0.0146	0.7947	0.7932	0.2613	0.0181	<.0001	0.2772	0.1403	0.5611	0.4311	<.0001	0.0004
Storage condition	–	0.7547	0.2183	–	0.4936	0.0519	–	0.4817	0.1700	–	0.0029	0.2947
Coating × Storage condition	–	0.4193	0.8948	–	0.0878	0.0500	–	0.1833	0.6858	–	0.3611	0.6519

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline root length (mm) prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.13. Effects of coating, storage condition, and their interaction on hillslope of cool-season turfgrass species across years in Run 1.

	Hillslope											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	7.71 a	6.54	7.11 a	6.66 a	7.04 a	6.17	6.37	6.59	12.21 a	11.40 b	10.47 a	8.02
Noncoated	4.97 b	6.28	5.77 b	5.59 b	5.81 b	6.26	5.75	6.37	6.06 b	5.87 a	7.86 b	7.64
Storage condition												
Indoor	6.34	6.61	6.40	6.13	6.30 b	5.53 b	6.06	6.86 a	6.21 b	8.64	9.55	7.63
Refrigerator	–	6.07	6.24	–	7.00 a	5.65 b	–	6.94 a	5.85 b	–	9.36	8.25
Shed	–	6.56	6.68	–	5.96 b	7.47 a	–	5.63 b	15.36 a	–	8.58	7.61
Coating × Storage condition												
Coated × Indoor	–	6.82	6.44 b	–	7.22	5.86 b	–	7.06	6.36 b	–	11.18	8.38 bac
Coated × Refrigerator	–	6.29	8.09 a	–	7.58	6.62 ba	–	7.09	6.22 b	–	10.07	9.30 a
Coated × Shed	–	6.51	6.80 b	–	6.31	6.03 b	–	5.60	24.06 a	–	10.16	6.40 d
Noncoated × Indoor	–	6.40	6.37 b	–	5.39	5.20 b	–	6.66	6.05 b	–	7.93	6.88 dc
Noncoated × Refrigerator	–	5.85	4.39 c	–	6.41	4.68 b	–	6.79	5.47 b	–	8.64	7.21 bdc
Noncoated × Shed	–	6.60	6.56 b	–	5.62	8.91 a	–	5.66	6.66 b	–	7.00	8.82 ba
<i>p</i> values												
Coating	0.0072	0.3317	0.0007	0.0483	0.0001	0.8778	0.2924	0.4482	<.0001	0.0172	<.0001	0.4290
Storage condition	–	0.2070	0.5331	–	0.0087	0.0370	–	0.0020	<.0001	–	0.2078	0.4701
Coating × Storage condition	–	0.6511	0.0004	–	0.1769	0.0167	–	0.7709	<.0001	–	0.2113	0.0028

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline hillslope values prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–). Hillslope (no units) describes the steepness of the sigmoidal germination curve.

Table B.14. Effects of coating, storage condition, and their interaction on hillslope of cool-season turfgrass species across years in Run 2.

	Hillslope											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	7.72 a	7.01 a	6.47	5.65 a	6.80 a	5.60	6.37	6.52 a	5.75	9.17 a	9.45 a	9.55
Noncoated	5.14 b	5.87 b	5.73	4.63 b	4.80 b	5.40	5.75	6.05 b	4.90	5.00 b	7.60 b	7.51
Storage condition												
Indoor	6.43	6.80	5.79 b	5.13	5.90	5.60	6.06	6.69 a	4.81 b	7.08	8.02	7.55 b
Refrigerator	–	6.08	5.34 b	–	5.80	5.30	–	5.86 b	4.42 b	–	8.83	7.57 b
Shed	–	6.45	7.17 a	–	5.60	5.60	–	6.31 ba	6.76 a	–	8.73	10.47 a
Coating × Storage condition												
Coated × Indoor	–	7.72	6.37	–	7.20	5.60	–	6.82	4.94	–	9.21	7.92
Coated × Refrigerator	–	6.60	5.49	–	6.40	6.00	–	6.22	4.84	–	9.93	8.16
Coated × Shed	–	6.73	7.54	–	6.70	5.10	–	6.53	7.48	–	9.20	12.56
Noncoated × Indoor	–	5.88	5.21	–	4.70	5.60	–	6.56	4.69	–	6.83	7.18
Noncoated × Refrigerator	–	5.55	5.19	–	5.20	4.50	–	5.50	3.99	–	7.73	6.97
Noncoated × Shed	–	6.17	6.79	–	4.50	6.00	–	6.10	6.03	–	8.25	8.38
<i>p</i> values												
Coating	0.0045	0.0007	0.0854	0.0121	<.0001	0.6094	0.2924	0.0480	0.0999	0.0305	<.0001	0.0503
Storage condition	–	0.1252	0.0056	–	0.6673	0.7030	–	0.0245	0.0028	–	0.1094	0.0376
Coating × Storage condition	–	0.1845	0.6861	–	0.1854	0.0578	–	0.6907	0.6114	–	0.1677	0.3078

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline hillslope values prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–). Hillslope (no units) describes the steepness of the sigmoidal germination curve.

Table B.15. Effects of coating, storage condition, and their interaction on top (%) of cool-season turfgrass species across years in Run 1.

	Top (%)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	96.9	93.1 a	87.2 a	94.5 a	89.1 a	70.1 a	85.1 a	69.5	50.1	84.0	78.2 b	65.5
Noncoated	91.1	88.4 b	82.6 b	82.9 b	80.4 b	53.9 b	79.8 b	66.8	47.1	85.5	84.8 a	66.3
Storage condition												
Indoor	94.0	92.2	90.1 a	88.7	90.5 a	81.1 b	82.5	79.7 a	67.6 b	84.7	84.6 a	77.9 b
Refrigerator	–	90.5	92.2 a	–	88.6 a	89.0 a	–	82.4 a	76.7 a	–	84.0 a	85.0 a
Shed	–	89.7	72.5 b	–	75.2 b	15.8 c	–	42.4 b	1.6 c	–	75.9 b	34.9 c
Coating × Storage condition												
Coated × Indoor	–	93.8	94.3	–	92.0 a	91.8	–	82.4	67.0	–	81.8 b	74.1 b
Coated × Refrigerator	–	92.0	94.5	–	91.3 ba	94.5	–	82.9	81.9	–	79.1 cb	81.4 ba
Coated × Shed	–	93.6	72.9	–	84.1 b	24.1	–	43.3	1.3	–	73.9 d	41.1 c
Noncoated × Indoor	–	90.5	85.9	–	89.0 ba	70.4	–	77.0	68.2	–	87.5 a	81.7 ba
Noncoated × Refrigerator	–	89.1	89.9	–	85.9 ba	83.7	–	81.8	71.3	–	89.0 a	88.6 a
Noncoated × Shed	–	85.7	72.0	–	66.3 c	7.6	–	41.6	1.8	–	77.9 c	28.6 d
<i>p</i> values												
Coating	0.0721	0.0009	0.0057	0.0024	0.0008	<.0001	0.0414	0.1423	0.2680	0.5257	<.0001	0.7676
Storage condition	–	0.2211	<.0001	–	<.0001	<.0001	–	<.0001	<.0001	–	<.0001	<.0001
Coating × Storage condition	–	0.1700	0.1400	–	0.0241	0.1731	–	0.5617	0.1468	–	0.0355	0.0125

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline top % values prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–). Top (%) indicates the estimated maximum germination percentage predicted by the sigmoidal regression model.

Table B.16. Effects of coating, storage condition, and their interaction on top (%) of cool-season turfgrass species across years in Run 2.

	Top (%)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	96.4 a	93.9 a	93.6 a	94.6	94.3 a	76.9 b	85.0 a	82.2 a	55.9 a	86.5	85.2 b	82.0
Noncoated	91.3 b	89.3 b	86.5 b	86.2	87.4 b	84.9 a	79.8 b	76.6 b	50.6 b	88.8	90.1 a	82.5
Storage condition												
Indoor	93.9	91.6 ba	92.3 a	90.4	91.7 a	81.3 b	82.4	81.5 a	63.8 a	87.7	86.4	83.7 a
Refrigerator	–	93.3 a	90.6 a	–	92.1 a	93.4 a	–	81.0 a	68.2 a	–	89.3	87.0 a
Shed	–	90.1 b	87.2 b	–	88.8 b	68.1 c	–	75.8 b	27.8 b	–	87.2	76.2 b
Coating × Storage condition												
Coated × Indoor	–	94.8	95.7	–	94.6	73.0 b	–	82.8	65.4	–	85.5 c	81.4 bc
Coated × Refrigerator	–	95.9	94.4	–	94.2	94.6 a	–	85.4	74.9	–	84.9 c	85.5 ba
Coated × Shed	–	91.1	90.8	–	94.1	63.1 b	–	78.5	27.6	–	85.0 c	79.2 c
Noncoated × Indoor	–	88.4	88.9	–	88.8	89.5a	–	80.2	62.3	–	87.2 cb	86.0 ba
Noncoated × Refrigerator	–	90.6	86.9	–	90.0	92.2 a	–	76.6	61.6	–	93.6 a	88.5 a
Noncoated × Shed	–	89.0	83.7	–	83.5	73.1 b	–	73.0	27.9	–	89.5 b	73.2 d
<i>p</i> values												
Coating	0.0094	<.0001	<.0001	0.0636	<.0001	0.0109	0.0414	0.0009	0.0441	0.4076	0.0001	0.6962
Storage condition	–	0.0090	0.0021	–	0.0399	<.0001	–	0.0062	<.0001	–	0.0681	<.0001
Coating × Storage condition	–	0.0669	0.9422	–	0.0596	0.0392	–	0.1982	0.0878	–	0.0275	0.0120

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline top % values prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–). Top (%) indicates the estimated maximum germination percentage predicted by the sigmoidal regression model.

Table B.17. Effects of coating, storage condition, and their interaction on average fresh weight (mg) of cool-season turfgrass species across years in Run 1.

	Average fresh weight (mg)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	0.0084	0.0094 a	0.0098 a	0.0111	0.0116 a	0.0125	0.0041	0.0040	0.0054 a	0.0016	0.0013	0.0017
Noncoated	0.0067	0.0068 b	0.0083 b	0.0091	0.0094 b	0.0113	0.0040	0.0035	0.0044 b	0.0015	0.0014	0.0021
Storage condition												
Indoor	0.0075	0.0077	0.0072 c	0.0101	0.0101	0.0125 a	0.0040	0.0037	0.0049	0.0016	0.0013	0.0021 a
Refrigerator	–	0.0077	0.0092 b	–	0.0112	0.0127 a	–	0.0039	0.0048	–	0.0014	0.0021 a
Shed	–	0.0088	0.0107 a	–	0.0103	0.0104 b	–	0.0037	–	–	0.0013	0.0014 b
Coating × Storage condition												
Coated × Indoor	–	0.0087	0.0076	–	0.0109	0.0142 a	–	0.0040 ba	0.0053	–	0.0013	0.0020
Coated × Refrigerator	–	0.0091	0.0101	–	0.0127	0.0134 ba	–	0.0047 a	0.0055	–	0.0012	0.0019
Coated × Shed	–	0.0102	0.0117	–	0.0111	0.0100 d	–	0.0033 b	–	–	0.0013	0.0013
Noncoated × Indoor	–	0.0067	0.0068	–	0.0094	0.0108 dc	–	0.0033 b	0.0045	–	0.0013	0.0022
Noncoated × Refrigerator	–	0.0063	0.0083	–	0.0096	0.0121 bc	–	0.0032 b	0.0042	–	0.0015	0.0023
Noncoated × Shed	–	0.0075	0.0097	–	0.0094	0.0109 dc	–	0.0040 ba	–	–	0.0013	0.0016
<i>p</i> values												
Coating	0.1292	0.0019	0.0139	0.0736	0.0002	0.0505	0.9766	0.1499	0.0032	0.9903	0.1575	0.0696
Storage condition	–	0.3204	0.0004	–	0.1580	0.0185	–	0.7227	0.7559	–	0.5761	0.0056
Coating × Storage condition	–	0.8703	0.6137	–	0.2950	0.0397	–	0.0453	0.3387	–	0.0884	0.8257

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline average fresh weight values prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.18. Effects of coating, storage condition, and their interaction on average fresh weight (mg) of cool-season turfgrass species across years in Run 2.

	Average fresh weight (mg)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	0.0081	0.0094 a	0.0075 a	0.0103	0.0106	0.0122 a	0.0042	0.0036	0.0039 a	0.0017	0.0020	0.0013 a
Noncoated	0.0073	0.0074 b	0.0058 b	0.0097	0.0101	0.0091 b	0.0047	0.0032	0.0029 b	0.0015	0.0016	0.0006 b
Storage condition												
Indoor	0.0077	0.0079	0.0064	0.0100	0.0096	0.0097 b	0.0044	0.0033	0.0032	0.0016	0.0017	0.0007 b
Refrigerator	–	0.0087	0.0066	–	0.0105	0.0117 a	–	0.0034	0.0034	–	0.0020	0.0011 a
Shed	–	0.0085	0.0071	–	0.0109	0.0105 b	–	0.0035	0.0036	–	0.0016	0.0010 a
Coating × Storage condition												
Coated × Indoor	–	0.0089	0.0071	–	0.0107 a	0.0109	–	0.0036	0.0039	–	0.0022	0.0007 b
Coated × Refrigerator	–	0.0102	0.0077	–	0.0099 ba	0.0132	–	0.0035	0.0038	–	0.0022	0.0017 a
Coated × Shed	–	0.0089	0.0078	–	0.0111a	0.0124	–	0.0038	0.0040	–	0.0016	0.0016 a
Noncoated × Indoor	–	0.0068	0.0057	–	0.0086 b	0.0085	–	0.0031	0.0025	–	0.0012	0.0007 b
Noncoated × Refrigerator	–	0.0071	0.0055	–	0.0110 a	0.0102	–	0.0033	0.0031	–	0.0018	0.0006 b
Noncoated × Shed	–	0.0081	0.0063	–	0.0107 a	0.0086	–	0.0033	0.0031	–	0.0016	0.0005 b
<i>p</i> values												
Coating	0.2821	0.0017	0.0070	0.1327	0.2677	<.0001	0.2199	0.0587	<.0001	0.3275	0.0768	<.0001
Storage condition	–	0.4434	0.5673	–	0.0654	0.0040	–	0.6897	0.1178	–	0.4310	0.0007
Coating × Storage condition	–	0.2336	0.8366	–	0.0155	0.3654	–	0.7211	0.0633	–	0.2732	<.0001

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline average fresh weight values prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.19. Effects of coating, storage condition, and their interaction on average dry weight (mg) of cool-season turfgrass species across years in Run 1.

	Average dry weight (mg)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	0.0005	0.0005	0.0006 a	0.0008	0.0009 a	0.0008 a	0.0003	0.0003	0.0003	0.0001	0.0001	0.0001
Noncoated	0.0004	0.0005	0.0004 b	0.0007	0.0008 b	0.0006 b	0.0003	0.0003	0.0003	0.0001	0.0001	0.0001
Storage condition												
Indoor	0.0005	0.0006	0.0005	0.0007	0.0008	0.0007 a	0.0003	0.0003	0.0003	0.0001	0.0001	0.0001 ba
Refrigerator	–	0.0005	0.0005	–	0.0009	0.0008 a	–	0.0003	0.0003	–	0.0001	0.0001 a
Shed	–	0.0005	0.0005	–	0.0008	0.0006 b	–	0.0003		–	0.0001	0.0001 b
Coating × Storage condition												
Coated × Indoor	–	0.0006	0.0005	–	0.0008	0.0008	–	0.0003	0.0003	–	0.0001	0.0001
Coated × Refrigerator	–	0.0005	0.0006	–	0.0009	0.0008	–	0.0003	0.0003	–	0.0001	0.0001
Coated × Shed	–	0.0005	0.0006	–	0.0009	0.0007	–	0.0003	–	–	0.0001	0.0001
Noncoated × Indoor	–	0.0005	0.0004	–	0.0008	0.0007	–	0.0003	0.0003	–	0.0001	0.0001
Noncoated × Refrigerator	–	0.0004	0.0004	–	0.0008	0.0008	–	0.0003	0.0003	–	0.0001	0.0001
Noncoated × Shed	–	0.0005	0.0005	–	0.0007	0.0004	–	0.0003	–	–	0.0001	0.0000
<i>p</i> values												
Coating	0.2934	0.0606	<.0001	0.1059	0.0012	0.0127	0.4358	0.2250	0.7109	0.4915	0.2263	0.6915
Storage condition	–	0.0539	0.0773	–	0.3199	0.0185	–	0.5694	0.0588	–	0.5973	0.0357
Coating × Storage condition	–	0.6264	0.0662	–	0.2607	0.0753	–	0.4891	0.4673	–	0.6041	0.3626

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline average dry weight values prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Table B.20. Effects of coating, storage condition, and their interaction on average dry weight (mg) of cool-season turfgrass species across years in Run 2.

	Average dry weight (mg)											
	Perennial ryegrass			Tall fescue			Strong creeping red fescue			Kentucky bluegrass		
	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2	Year 0	Year 1	Year 2
Coating												
Coated	0.0005	0.0006 a	0.00054 a	0.0007	0.0008 a	0.0009 a	0.0003	0.0004	0.0004 a	0.0001	0.0001	0.0001
Noncoated	0.0005	0.0005 b	0.00059 b	0.0007	0.0007 b	0.0008 b	0.0003	0.0003	0.0003 b	0.0001	0.0001	0.0001
Storage condition												
Indoor	0.0005	0.0005	0.0005	0.0007	0.0007	0.0008 b	0.0003	0.0003	0.0003 b	0.0001	0.0001	0.0001
Refrigerator	–	0.0006	0.0005	–	0.0007	0.0009 a	–	0.0003	0.0003 b	–	0.0001	0.0001
Shed	–	0.0005	0.0005	–	0.0008	0.0009 a	–	0.0003	0.0004 a	–	0.0001	0.0001
Coating × Storage condition												
Coated × Indoor	–	0.0005	0.0005	–	0.0008 a	0.0008	–	0.0004	0.0004	–	0.0001	0.0001
Coated × Refrigerator	–	0.0007	0.0006	–	0.0007 a	0.0010	–	0.0003	0.0003	–	0.0001	0.0001
Coated × Shed	–	0.0006	0.0005	–	0.0008 a	0.0010	–	0.0004	0.0004	–	0.0001	0.0001
Noncoated × Indoor	–	0.0005	0.0005	–	0.0006 b	0.0008	–	0.0003	0.0003	–	0.0001	0.0001
Noncoated × Refrigerator	–	0.0005	0.0005	–	0.0008 a	0.0008	–	0.0003	0.0003	–	0.0001	0.0001
Noncoated × Shed	–	0.0005	0.0005	–	0.0007 a	0.0008	–	0.0003	0.0004	–	0.0001	0.0001
<i>p</i> values												
Coating	0.4940	0.0098	0.0449	0.3292	0.0246	0.0004	0.5535	0.1569	0.0007	0.7368	0.5472	0.8347
Storage condition	–	0.4581	0.4697	–	0.1145	0.0041	–	0.4299	0.0003	–	0.9120	0.1150
Coating × Storage condition	–	0.1237	0.7202	–	0.0226	0.2000	–	0.9588	0.1677	–	0.2938	0.1950

Note: Means within a column for each main and interaction effect followed by the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's protected LSD test. Bolded *p* values indicate statistical significance ($p \leq 0.05$). Year 0 represents baseline average dry weight values prior to storage treatment, storage conditions were not applicable, as indicated by a dash (–).

Appendix C - Additional Figures and Tables for Chapter 4



Figure C.1. Greenhouse experimental setup for evaluating seed coating, irrigation regime, and soil type effects on turfgrass establishment at the Throckmorton Plant Science Center greenhouses, Kansas State University.



Figure C.2. Greenhouse study preparation. (A) Pots lined with cloth fabric before adding sand. (B) Pots filled with different soil types. (C) Experiment 1 pots arranged to evaluate the effects of seed coating and irrigation amount using the same soil type. (D) Experiment 2 pots arranged to evaluate the effects of seed coating and irrigation frequency across different soil types.

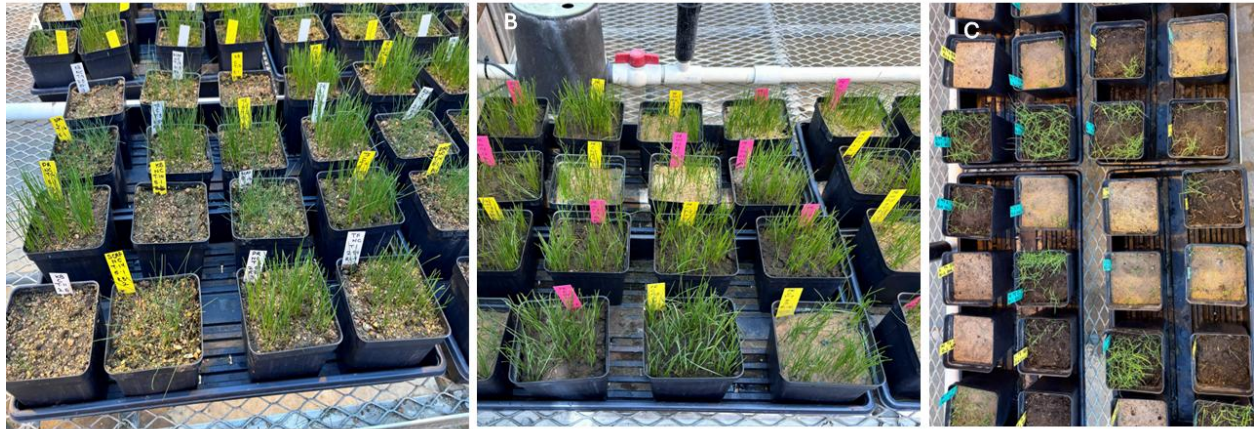


Figure C.3. Greenhouse turfgrass establishment in Experiments 1, 2, and 3. (A) Experiment 1 evaluating seed coating and irrigation amount effects. (B) Experiment 2 evaluating seed coating and irrigation frequency effects across soil types. (C) Experiment 3 evaluating bermudagrass establishment under different soil type and treatment combinations.



Figure C.4. Digital image collection for turfgrass cover assessment (percent green cover) using digital camera.

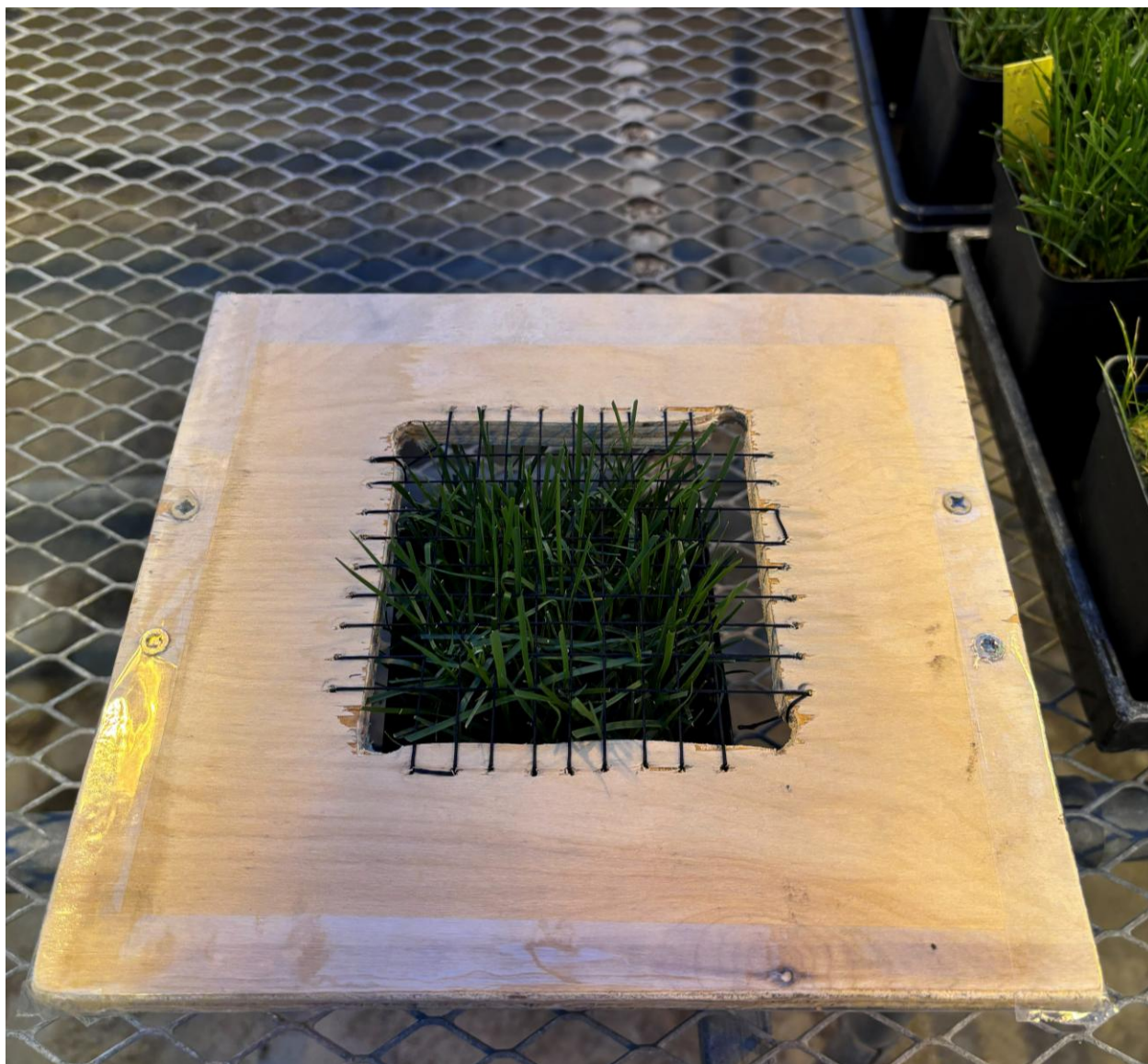


Figure C.5. Greenhouse turfgrass cover assessment using a grid-count method. A 9×9 grid frame with 81 intersections was placed over each pot, and turfgrass presence at each intersection was recorded to calculate turfgrass cover.

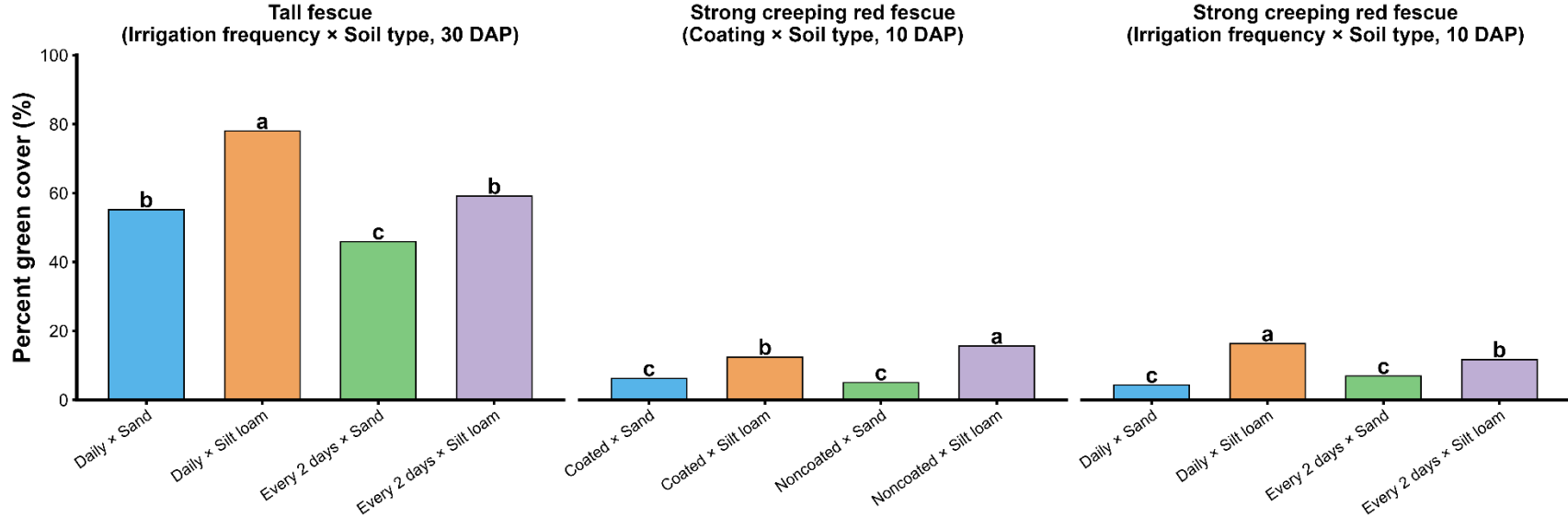


Figure C.6. Effects of irrigation frequency × soil type and seed coating × soil type interactions on percent green cover (%) in tall fescue and strong creeping red fescue at selected days after planting (DAP) in Experiment 2. *Note:* Bars represent treatment means. Irrigation frequency treatments were daily and every 2 d, and soil types were sand and silt loam. Coating treatments included coated and noncoated seed. Letters above bars within each panel indicate significant differences among treatments at each DAP according to Fisher's protected LSD test ($\alpha = 0.05$). Percent green cover was measured using digital image analysis.

Table C.1. Effect of seed coating, irrigation amount, and their interaction on seedling emergence of cool-season turfgrass species in Experiment 1

Species	Perennial ryegrass	Tall fescue	Strong creeping red fescue	Kentucky bluegrass
Seed coating	Seedling emergence (days)			
Coated	4.0	4.2	4.6	6.6 a
Noncoated	4.0	4.1	4.1	6.1 b
Irrigation amount				
2.5 mm	4.0	4.0	4.3	6.3
5.1 mm	4.0	4.3	4.4	6.4
<i>p</i> values				
Seed coating	1.0000	0.7334	0.0800	0.0062
Irrigation amount	1.0000	0.0974	0.7965	0.6729
Seed coating × Irrigation amount	1.0000	0.7334	0.2043	0.2118

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$.

Table C.2. Effect of seed coating, irrigation frequency, soil type, and their interaction on seedling emergence of cool-season turfgrass species in Experiment 2.

Species	Perennial ryegrass	Tall fescue	Strong creeping red fescue	Kentucky bluegrass
Seed coating	Seedling emergence (days)			
Coated	4.0	4.1	5.0	6.4
Noncoated	4.0	4.1	4.7	6.4
Irrigation frequency				
Daily	4.0	4.1	4.8	6.5
Every 2 days	4.0	4.1	4.9	6.4
Soil type				
Sand	4.0	4.2 a	5.1 a	6.7 a
Silt loam	4.0	4.0 b	4.5 b	6.1 b
<i>p</i> values				
Seed coating	1.0000	1.0000	0.1262	0.7985
Irrigation frequency	1.0000	1.0000	0.5370	0.4449
Seed coating × Irrigation frequency	1.0000	0.3706	0.2194	0.4449
Soil type	1.0000	0.0091	0.0161	<.0001
Seed coating × Soil type	1.0000	1.0000	0.5370	0.4449
Irrigation frequency × Soil type	1.0000	1.0000	0.3555	0.0249
Seed coating × Irrigation frequency × Soil type	1.0000	0.3706	0.3555	0.4449

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$.

Table C.3. Interaction effect of irrigation frequency and soil type on seedling emergence of cool-season turfgrass species in Experiment 2.

Species	Perennial ryegrass	Tall fescue	Strong creeping red fescue	Kentucky bluegrass
Irrigation frequency × Soil type	Seedling emergence (days)			
Daily × Sand	4.0	4.2	5.0	6.6 ba
Daily × Silt loam	4.0	4.0	4.6	6.3 b
Every 2 days × Sand	4.0	4.2	5.3	6.8 a
Every 2 days × Silt loam	4.0	4.0	4.6	6.0 c
<i>p values</i>				
Irrigation frequency × Soil type	1.0000	1.0000	0.3555	0.0249

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$.

Table C.4. Effect of seed coating, irrigation frequency, soil type, and their interaction on seedling emergence of bermudagrass in Experiment 3.

Species	Bermudagrass
	Seedling emergence (days)
Seed coating	
Coated	19.3
Noncoated	17.7
Irrigation frequency	
Daily	8.1 b
Every 3 days	28.8 a
Soil type	
Sand	27.2 a
Silt loam	9.8 b
<i>p</i> values	
Seed coating	0.2810
Irrigation frequency	<.0001
Seed coating × Irrigation frequency	0.2107
Soil type	<.0001
Seed coating × Soil type	0.2620
Irrigation frequency × Soil type	<.0001
Seed coating × Irrigation frequency × Soil type	0.2620

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$.

Table C.5. Interaction effect of irrigation frequency and soil type on seedling emergence of bermudagrass in Experiment 3.

Species	Bermudagrass
Irrigation frequency × Soil type	Seedling emergence (days)
Daily × Sand	9.3 cb
Daily × Silt loam	7.0 c
Every 3 days × Sand	45.1 a
Every 3 days × Silt loam	12.6 b
<i>p</i> values	
Irrigation frequency × Soil type	<.0001

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$.

Table C.6. Effect of seed coating, irrigation amount, and their interaction on visual turf cover (%) at 10, 20, 30, 40, and 50 days after planting in perennial ryegrass, tall fescue, and strong creeping red fescue in Experiment 1.

Species	Perennial ryegrass					Tall fescue					Strong creeping red fescue				
Factors	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP
Seed coating	Visual turf cover (%)														
Coated	22.3	40.9	50.7	62.6	73.0	18.8 a	35.6	45.8	64.9 a	78.0 a	13.6	31.0	39.1	54.9	64.3
Noncoated	20.2	39.3	47.8	59.1	69.9	14.6 b	29.4	38.3	56.9 b	71.4 b	12.3	26.7	37.4	51.9	62.3
Irrigation amount															
2.5 mm	20.1	29.9 b	41.7 b	61.1	75.1 a	16.3	25.1 b	35.4 b	59.3	75.4	13.7	22.4	32.6	51.1	62.6
5.1 mm	22.4	50.2 a	56.8 a	60.6	67.8 b	17.1	39.8 a	48.6 a	62.5	73.9	12.2	35.3	43.9	55.8	63.9
<i>p</i> values															
Seed coating	0.1883	0.6633	0.3798	0.0622	0.2496	0.0083	0.1074	0.0606	0.0040	0.0179	0.2576	0.2489	0.6223	0.1021	0.2730
Irrigation amount	0.1432	0.0001	0.0001	0.7826	0.0101	0.6068	0.0005	0.0021	0.2102	0.5711	0.1768	0.0016	0.0034	0.0126	0.4482
Seed coating × Irrigation amount	0.1645	0.7885	0.4211	0.3733	0.9628	0.6068	0.5382	0.8850	0.6957	0.7765	0.3071	0.9325	0.9157	0.2405	0.0215

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.7. Interaction effect of seed coating and irrigation amount on visual turf cover (%) at 10, 20, 30, 40, and 50 days after planting in strong creeping red fescue in Experiment 1.

Species	Strong creeping red fescue				
Factors	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP
Seed coating × Irrigation amount	Visual turf cover (%)				
Coated × 2.5 mm	13.8	24.4	33.3	51.5	61.4 b
Coated × 5.1 mm	13.4	37.6	45.0	58.4	67.1 a
Noncoated × 2.5 mm	13.6	20.4	31.9	50.6	63.8 ba
Noncoated × 5.1 mm	11.0	33.0	42.9	53.3	60.8 b
<i>p</i> values					
Seed coating × Irrigation amount	0.3071	0.9325	0.9157	0.2405	0.0215

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.8. Effect of seed coating, irrigation frequency and soil type, and their interaction on visual turf cover (%) at 10, 20, 30, 40, and 50 days after planting in perennial ryegrass and tall fescue in Experiment 2.

Species	Perennial ryegrass					Tall fescue				
Factors	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP
Seed coating	Visual turf cover (%)									
Coated	21.6 a	44.8	56.5	68.8	75.1	19.6	40.8	51.4	68.8	79.4
Noncoated	18.3 b	42.0	52.6	64.9	70.9	17.8	40.8	52.2	68.0	78.0
Irrigation frequency										
Daily	19.7	46.2	57.1	66.9	73.6	19.0	43.5	54.8	70.0	80.0
Every 2 days	20.2	40.7	52.0	66.8	72.5	18.4	38.0	48.8	66.8	77.4
Soil type										
Sand	19.2	37.7 b	45.8 b	55.6 b	61.0 b	16.3 b	38.5	46.0 b	59.5 b	67.5 b
Silt loam	20.7	49.1 a	63.3 a	78.1 a	85.1 a	21.2 a	43.1	57.6 a	77.3 a	89.9 a
<i>p</i> values										
Seed coating	0.0085	0.4641	0.3043	0.1424	0.0687	0.2138	1.0000	0.8220	0.7793	0.4175
Irrigation frequency	0.7247	0.1642	0.1767	0.9619	0.6319	0.6550	0.0728	0.1044	0.2420	0.1549
Seed coating × Irrigation frequency	0.9598	0.7377	0.7226	0.8297	0.8802	0.8933	0.8848	0.9724	0.5986	0.2493
Soil type	0.2301	0.0052	<.0001	<.0001	<.0001	0.0009	0.1297	0.0022	<.0001	<.0001
Seed coating × Soil type	0.6151	0.9364	0.7226	0.9238	0.7528	0.8231	0.8848	0.9448	0.630	0.6909
Irrigation frequency × Soil type	0.1483	0.4936	0.6500	0.9619	0.7321	0.9643	0.6344	0.5568	0.8138	0.3610
Seed coating × Irrigation frequency × Soil type	0.6508	0.7986	0.494	0.3292	0.1702	0.4753	1.0000	0.8490	0.9018	0.6162

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.9. Effect of seed coating, irrigation frequency and soil type, and their interaction on visual turf cover (%) at 10, 20, 30, 40, and 50 days after planting in strong creeping red fescue and Kentucky bluegrass in Experiment 2.

Species	Strong creeping red fescue					Kentucky bluegrass				
Factors	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP
Seed coating	Visual turf cover (%)									
Coated	12.6 b	34.8	41.7	53.3	66.6	6.1	29.4	40.0	50.8	61.3
Noncoated	14.4 a	34.8	42.2	53.7	68.5	5.3	23.8	33.9	46.6	54.2
Irrigation frequency										
Daily	13.3	36.7	44.0	54.9	68.6	5.7	28.3	39.4	50.6	58.8
Every 2 days	13.7	32.9	39.8	52.1	66.5	5.8	24.9	34.6	46.8	56.7
Soil type										
Sand	11.4 b	32.8	39.1 b	48.3 b	58.5 b	4.6 b	22.9 b	33.0 b	43.5 b	50.8 b
Silt loam	15.7 a	36.8	44.8 a	58.7 a	76.6 a	6.8 a	30.3 a	40.9 a	53.8 a	64.7 a
<i>p</i> values										
Seed coating	0.0126	0.9874	0.8433	0.8367	0.3473	0.1955	0.0908	0.1031	0.2877	0.1081
Irrigation frequency	0.6201	0.0564	0.0795	0.1348	0.3324	0.7942	0.2956	0.1981	0.3326	0.6249
Seed coating × Irrigation frequency	0.3019	0.3701	0.4078	0.8907	0.8928	0.3236	0.8572	0.7618	0.8482	0.7191
Soil type	<.0001	0.0457	0.0188	<.0001	<.0001	0.0005	0.027	0.0362	0.0107	0.0022
Seed coating × Soil type	0.0078	0.625	0.5023	0.631	0.8223	0.5665	0.6161	0.6137	0.6554	0.5557
Irrigation frequency × Soil type	0.1943	0.2521	0.438	0.4931	0.7306	0.5665	0.6029	0.6986	0.6326	0.8855
Seed coating × Irrigation frequency × Soil type	0.5582	0.7885	0.8639	0.8367	0.7082	0.9584	0.902	0.9463	0.8607	0.7191

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.10. Interaction effect of seed coating and soil type on visual turf cover (%) at 10, 20, 30, 40, and 50 days after planting in strong creeping red fescue in Experiment 2.

Species	Strong creeping red fescue				
Factors	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP
Seed coating × Soil type	Visual turf cover (%)				
Coated × Sand	11.4 c	33.3	39.6	48.6	57.8
Coated × Silt loam	13.8 b	36.3	43.8	58.1	75.4
Noncoated × Sand	11.3 c	32.3	38.5	48.1	59.3
Noncoated × Silt loam	17.5 a	37.3	45.8	59.3	77.8
<i>p</i> values					
Seed coating × Irrigation amount	0.0078	0.6250	0.5023	0.6310	0.8223

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.11. Effect of seed coating, irrigation frequency, soil type, and their interaction on visual turf cover (%) at 15, 25, 35 and 45 days after planting in bermudagrass in Experiment 3.

Species	Bermudagrass			
Factors	15 DAP	25 DAP	35 DAP	45 DAP
Seed coating	Visual turf cover (%)			
Coated	1.8 b	5.5	12.3 b	17.1 b
Noncoated	2.8 a	8.4	17.6 a	23.7 a
Irrigation frequency				
Daily	4.1 a	12.5 a	27.1 a	36.4 a
Every 3 days	0.5 b	1.4 b	2.8 b	4.4 b
Soil type				
Sand	1.1 b	2.4 b	5.0 b	6.9 b
Silt loam	3.5 a	11.4 a	24.8 a	33.9 a
<i>p</i> values				
Seed coating	0.0169	0.0512	0.0161	0.0109
Irrigation frequency	<.0001	<.0001	<.0001	<.0001
Seed coating × Irrigation frequency	0.0917	0.2607	0.1645	0.1285
Soil type	<.0001	<.0001	<.0001	<.0001
Seed coating × Soil type	0.1195	0.3605	0.1404	0.1844
Irrigation frequency × Soil type	0.0014	<.0001	<.0001	<.0001
Seed coating × Irrigation frequency × Soil type	0.4088	0.9489	0.6751	0.8043

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.12. Effect of seed coating, irrigation amount, and their interaction on percent green cover (%) at 10, 20, 30, 40, and 50 days after planting in perennial ryegrass, tall fescue, and strong creeping red fescue in Experiment 1.

Species	Perennial ryegrass					Tall fescue					Strong creeping red fescue				
Factors	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP
Seed coating	Percent green cover (%)														
Coated	28.3 a	49.9 a	63.9	70.7 a	62	15.5 a	37.8 a	55.7 a	71.1 a	73.1	8.4	26.9	38.3	52.3	52.8
Noncoated	21.4 b	44.0 b	58.9	65.3 b	60.2	11.3 b	30.7 b	47.9 b	66.1 b	69.3	8.9	23.1	35.4	48.8	51.4
Irrigation amount															
2.5 mm	21.4 b	29.4 b	46.6 b	68.8	69.7 a	13	22.0 b	37.2 b	65.3 b	75.9 a	8.6	15.3 b	25.4 b	47.8 b	53.3
5.1 mm	28.3 a	64.4 a	76.2 a	67.2	52.5 b	13.8	46.5 a	66.4 a	71.9 a	66.5 b	8.6	34.8 a	48.2 a	53.3 a	50.9
<i>p</i> values															
Seed coating	0.0112	0.0044	0.13	0.0418	0.4287	0.0379	0.0006	0.008	0.036	0.1674	0.5737	0.0569	0.2171	0.1352	0.5342
Irrigation amount	0.0011	<.0001	<.0001	0.5279	<.0001	0.6935	<.0001	<.0001	0.0069	0.0017	0.9927	<.0001	<.0001	0.0231	0.2964
Seed coating × Irrigation amount	0.8288	0.4545	0.1709	0.3198	0.7219	0.5739	0.5190	0.8854	0.7169	0.5456	0.4242	0.7208	0.6804	0.8564	0.6286

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.13. Effect of seed coating, irrigation frequency, soil type, and their interaction on percent green cover (%) at 10, 20, 30, 40, and 50 days after planting in perennial ryegrass and tall fescue in Experiment 2.

Species	Perennial ryegrass					Tall fescue				
Factors	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP
Seed coating	Percent green cover (%)									
Coated	42.2 a	63.4 a	69.9	72.4	22.3	12.6	42.2	59.4	75.4	78.4
Noncoated	33.7 b	56.6 b	67.1	71.6	18.6	12.4	40.1	59.6	76.2	79.9
Irrigation frequency										
Daily	21.1	61.8 a	71.5 a	75.2	71.3	13.5	46.8 a	66.6 a	77.5	79.5
Every 2 days	19.8	45.9 b	59.7 b	75.3	73.9	11.6	35.5 b	52.5 b	74.0	78.8
Soil type										
Sand	15.2 b	49.5 b	57.3 b	63.7 b	57.9 b	5.9 b	38.0 b	50.5 b	61.8 b	65.5 b
Silt loam	25.7 a	58.2 a	73.9 a	86.7 a	87.3 a	19.1 a	44.4 a	68.5 a	89.8 a	92.8 a
<i>p</i> values										
Seed coating	0.0999	0.0255	0.0540	0.5236	0.9084	0.9010	0.3013	0.9470	0.7652	0.5589
Irrigation frequency	0.5625	<.0001	0.0001	0.9688	0.3550	0.3762	<.0001	<.0001	0.1765	0.7630
Seed coating × Irrigation frequency	0.9214	0.3032	0.4888	0.9075	0.7710	0.7507	0.4118	0.7453	0.5487	0.7435
Soil type	<.0001	0.0053	<.0001	<.0001	<.0001	<.0001	0.0025	<.0001	<.0001	<.0001
Seed coating × Soil type	0.2193	0.6327	0.5094	0.3957	0.8785	0.9219	0.7146	0.6468	0.5901	0.8042
Irrigation frequency × Soil type	0.1989	0.3336	0.0603	0.9194	0.7931	0.6190	0.8035	0.0357	0.8781	0.4833
Seed coating × Irrigation frequency × Soil type	0.7020	0.3042	0.0678	0.1857	0.2071	0.9628	0.3608	0.7434	0.7306	0.9454

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.14. Effect of seed coating, irrigation frequency, soil type, and their interaction on percent green cover (%) at 10, 20, 30, 40, and 50 days after planting (DAP) in strong creeping red fescue and Kentucky bluegrass in Experiment 2.

Species	Strong creeping red fescue					Kentucky bluegrass				
Factors	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP	10 DAP	20 DAP	30 DAP	40 DAP	50 DAP
Seed coating	Percent green cover (%)									
Coated	9.3	33.3	48.0	61.7	65.2	1.0	23.5	45.1 a	61.0	67.4
Noncoated	10.3	33.4	46.1	59.3	64.9	1.1	18.6	37.2 b	54.2	62.4
Irrigation frequency										
Daily	10.3	37.9 a	53.3 a	61.7	65.3	0.6 b	24.0 a	45.3 a	60.4	65.5
Every 2 days	9.3	28.8 b	40.8 b	59.3	64.8	1.4 a	18.2 b	37.1 b	54.9	64.3
Soil type										
Sand	5.6 b	28.1 b	40.1 b	52.5 b	53.1 b	1.1	15.3 b	28.5 a	47.0 b	53.2 b
Silt loam	14.0 a	38.6 a	54.0 a	68.5 a	77.1 a	1.0	26.8 a	53.8 b	68.2 a	76.6 a
<i>p</i> values										
Seed coating	0.3209	0.9383	0.5101	0.4346	0.8867	0.7939	0.0671	0.0028	0.1324	0.2825
Irrigation frequency	0.3472	<.0001	<.0001	0.4313	0.8715	0.0039	0.0299	0.002	0.2272	0.7869
Seed coating × Irrigation frequency	0.4716	0.6898	0.5591	0.7892	0.9961	0.5809	0.9185	0.4357	0.5057	0.7088
Soil type	<.0001	<.0001	<.0001	<.0001	<.0001	0.6729	<.0001	<.0001	<.0001	<.0001
Seed coating × Soil type	0.0347	0.1291	0.3911	0.3864	0.8122	0.3259	0.8031	0.1546	0.5006	0.5139
Irrigation frequency × Soil type	0.0008	0.2882	0.075	0.4648	0.9247	0.7961	0.7876	0.0026	0.5425	0.5949
Seed coating × Irrigation frequency × Soil type	0.9423	0.9243	0.7461	0.5249	0.7847	0.8017	0.6342	0.9233	0.8873	0.9424

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.15. Effect of seed coating, irrigation frequency, soil type, and their interaction on percent green cover (%) at 15, 25, 35 and 45 days after planting in bermudagrass in Experiment 3.

Species	Bermudagrass			
Factors	15 DAP	25 DAP	35 DAP	45 DAP
Seed coating	Percent green cover (%)			
Coated	2.1	8.8	16.3	13.6
Noncoated	3.9	12.3	19.0	15.1
Irrigation frequency				
Daily	5.4 a	19.4 a	33.3 a	24.5 a
Every 3 days	0.7 b	1.7 b	2.1 b	4.2 b
Soil type				
Sand	0.8 b	2.2 b	5.4 b	6.2 b
Silt loam	5.3 a	18.8 a	29.9 a	22.5 a
<i>p</i> values				
Seed coating	0.0654	0.0725	0.248	0.7065
Irrigation frequency	<.0001	<.0001	<.0001	<.0001
Seed coating × Irrigation frequency	0.2751	0.1716	0.3209	0.7607
Soil type	<.0001	<.0001	<.0001	<.0001
Seed coating × Soil type	0.2128	0.4269	0.875	0.9047
Irrigation frequency × Soil type	0.0017	<.0001	<.0001	0.0400
Seed coating × Irrigation frequency × Soil type	0.6322	0.7246	0.9932	0.8486

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.16. Interaction effect of irrigation frequency $\times$ soil type on percent green cover (%) at 15, 25, 35 and 45 days after planting in bermudagrass in Experiment 3.

Species	Bermudagrass			
	15 DAP	25 DAP	35 DAP	45 DAP
Irrigation frequency $\times$ Soil type	Percent green cover (%)			
Daily $\times$ Sand	1.6 b	4.4 b	10.8 b	12.4 b
Daily $\times$ Silt loam	9.2 a	34.3 a	55.7 a	36.6 a
Every 3 days $\times$ Sand	0 b	0 b	0 c	0 c
Every 3 days $\times$ Silt loam	1.3 b	3.3 b	4.1 c	8.4 cb
<i>p</i> values				
Irrigation frequency $\times$ Soil type	0.0017	<.0001	<.0001	0.0400

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.17. Effect of seed coating, irrigation amount, and their interaction on grid count (%) at 15, 25, 35, and 45 days after planting in perennial ryegrass and tall fescue in Experiment 1.

	Perennial ryegrass				Tall fescue			
	Grid count (turf cover %)							
	15 DAP	25 DAP	35 DAP	45 DAP	15 DAP	25 DAP	35 DAP	45 DAP
Seed coating								
Coated	60.6	67.8	75.7	81.6	58.5 a	68.4	75.2 a	83.3 a
Noncoated	53.9	65.7	72.6	78.8	42.1 b	57.4	60.5 b	69.2 b
Irrigation amount								
2.5 mm	50.9 b	57.6 b	70.2	80.5	48.2	54.7 b	61.3 b	72.2
5.1 mm	63.6 a	76.0 a	78.1	79.9	52.3	71.1 a	74.4 a	80.3
<i>p</i> values								
Seed coating	0.0881	0.6986	0.6253	0.5611	0.0002	0.0881	0.0144	0.0027
Irrigation amount	0.0065	0.0207	0.3627	0.6862	0.1519	0.0198	0.0260	0.0501
Seed coating × Irrigation amount	0.3600	0.7541	0.6509	0.2825	0.1296	0.6568	0.8257	0.0537

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.18. Effect of seed coating, irrigation amount, and their interaction on grid count (%) at 15, 25, 35, and 45 days after planting in strong creeping red fescue and Kentucky bluegrass in Experiment 1.

	Strong creeping red fescue				Kentucky bluegrass			
	Grid count (turf cover %)							
	15 DAP	25 DAP	35 DAP	45 DAP	15 DAP	25 DAP	35 DAP	45 DAP
Seed coating								
Coated	40.0	55.9	66.0	77.8	21.7	31.9	45.4	57.8
Noncoated	40.3	51.6	64.9	77.3	18.5	28.8	40.7	54.9
Irrigation amount								
2.5 mm	38.7	52.4	61.0	75.8	21.5	30.6	41.4	58.6
5.1 mm	41.6	55.1	69.9	79.3	18.7	30.1	44.7	54.1
<i>p values</i>								
Seed coating	0.9754	0.4106	0.8401	0.8624	0.1786	0.5036	0.4435	0.6770
Irrigation amount	0.2972	0.6408	0.1246	0.1993	0.1313	0.8932	0.5138	0.2848
Seed coating × Irrigation amount	0.3704	0.6582	0.4670	0.0128	0.7632	0.8459	0.9813	0.2061

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.19. Interaction effect of seed coating $\times$ irrigation amount on grid count (turf cover %) at 15, 25, 35 and 45 days after planting in strong creeping red fescue in Experiment 1.

Strong creeping red fescue				
Factors	Grid count (turf cover %)			
Seed coating $\times$ Irrigation amount	15 DAP	25 DAP	35 DAP	45 DAP
Coated $\times$ 2.5 mm	37.2	52.2	59	72.7 b
Coated $\times$ 5.1 mm	42.7	59.6	73.1	82.9 a
Noncoated $\times$ 2.5 mm	40.1	52.6	63.1	78.9 ba
Noncoated $\times$ 5.1 mm	40.4	50.6	66.7	75.8 ba
<i>p values</i>				
Seed coating $\times$ Irrigation amount	0.3704	0.6582	0.467	0.0128

Note: Means within a column with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.20. Effect of seed coating, irrigation frequency, soil type and their interactions on grid count (turf cover %) at 15, 25, 35, and 45 days after planting (DAP) in perennial ryegrass and tall fescue in Experiment 2.

	Perennial ryegrass				Tall fescue			
	15 DAP	25 DAP	35 DAP	45 DAP	15 DAP	25 DAP	35 DAP	45 DAP
Seed coating	Grid count (turf cover)							
Coated	61.7	67.8	72.6	81.3	53.8	67.0	72.3	83.6
Noncoated	55.5	62.3	67.8	79.5	49.8	63.3	72.1	83.4
Irrigation frequency								
Daily	56.4	66.7	72.2	81.6	51.0	68.4	74.8	86.0 a
Every 2 days	60.8	63.4	68.1	79.2	52.6	61.9	69.5	81.1 b
Soil type								
Sand	52.4 b	60.1	62.3 b	71.6 b	47.0	63.9	65.5 b	76.7 b
Silt loam	64.8 a	70.0	78.0 a	89.2 a	56.6	66.5	78.9 a	90.4 a
<i>p</i> values								
Seed coating	0.0673	0.1389	0.2696	0.5394	0.2858	0.4012	0.7702	0.9361
Irrigation frequency	0.2397	0.5995	0.4448	0.5693	0.7530	0.3426	0.1813	0.0311
Seed coating × Irrigation frequency	0.3336	0.5127	0.8064	0.2625	0.9562	0.9258	0.9728	0.5163
Soil type	0.0188	0.1122	0.0054	<.0001	0.0456	0.7501	0.0043	<.0001
Seed coating × Soil type	0.4537	0.7993	0.8277	0.5568	0.5051	0.8425	0.8899	0.9674
Irrigation frequency × Soil type	0.3174	0.1919	0.4958	0.9306	0.7996	0.3879	0.5210	0.3377
Seed coating × Irrigation frequency × Soil type	0.3969	0.2193	0.2987	0.0634	0.9074	0.7623	0.6925	0.6650

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.21. Effect of seed coating, irrigation frequency, soil type and their interactions on grid count (turf cover %) at 15, 25, 35, and 45 days after planting (DAP) in strong creeping red fescue and Kentucky bluegrass in Experiment 2.

	Strong creeping red fescue				Kentucky bluegrass			
	15 DAP	25 DAP	35 DAP	45 DAP	15 DAP	25 DAP	35 DAP	45 DAP
Seed coating	Grid count (turf cover %)							
Coated	40.1	58.1	64.4	73.0	30.2	37.3	48.2	61.2 a
Noncoated	44.1	61.5	65.7	77.4	27.6	32.0	39.0	50.0 b
Irrigation frequency								
Daily	42.8	61.4	67.1	76.1	28.2	33.3	44.4	55.8
Every 2 days	41.4	58.2	63.0	74.3	29.7	36.0	42.7	55.4
Soil type								
Sand	38.4 b	56.6	56.6 b	65.5 b	26.9	29.5 b	34.7 b	41.6 b
Silt loam	45.8 a	63.0	73.5 a	84.9 a	31.0	39.8 a	52.5 a	69.6 a
<i>p</i> values								
Seed coating	0.0732	0.4697	0.7673	0.2039	0.4208	0.1546	0.0507	0.0101
Irrigation frequency	0.4061	0.6859	0.4662	0.7385	0.7389	0.2282	0.8300	0.5794
Seed coating × Irrigation frequency	0.4615	0.5171	0.8159	0.3428	0.3811	0.5513	0.9500	0.1941
Soil type	0.0021	0.3648	0.0011	<.0001	0.3864	0.0080	<.0001	<.0001
Seed coating × Soil type	0.5380	0.6447	0.8539	0.5493	0.6506	0.7447	0.9733	0.8329
Irrigation frequency × Soil type	0.3404	0.5383	0.9299	0.7212	0.2462	0.9921	0.4858	0.0635
Seed coating × Irrigation frequency × Soil type	0.6840	0.3313	0.3416	0.1222	0.5379	0.8341	0.8481	0.5006

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.22. Effect of seed coating, irrigation frequency, soil type and their interactions on grid count (turf cover %) at 15, 25, 35, and 45 days after planting in bermudagrass in Experiment 3.

Species	Bermudagrass			
Factors	15 DAP	25 DAP	35 DAP	45 DAP
Seed coating	Grid count (turf cover %)			
Coated	1.9 b	6.5 b	14.5	19.5 b
Noncoated	3.3 a	10.1 a	19.8	27.5 a
Irrigation frequency				
Daily	4.3 a	14.7 a	30.9 a	41.2 a
Every 3 days	0.9 b	2.0 b	3.5 b	5.8 b
Soil type				
Sand	0.8 b	2.5 b	5.2 b	7.5 b
Silt loam	4.4 a	14.2 a	29.2 a	39.5 a
<i>p</i> values				
Seed coating	0.0120	0.0320	0.0564	0.0054
Irrigation frequency	<.0001	<.0001	<.0001	<.0001
Seed coating × Irrigation frequency	0.2372	0.3529	0.3033	0.1437
Soil type	<.0001	<.0001	<.0001	<.0001
Seed coating × Soil type	0.0337	0.2113	0.2315	0.1230
Irrigation frequency × Soil type	0.0026	<.0001	<.0001	<.0001
Seed coating × Irrigation frequency × Soil type	0.4426	1.0000	0.7661	0.8793

Note: Means within a column within a main effect with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Table C.23. Interaction effect of irrigation frequency $\times$ soil type on grid count (turf cover %) at 15, 25, 35 and 45 days after planting in bermudagrass in Experiment 3.

Species	Bermudagrass			
	15 DAP	25 DAP	35 DAP	45 DAP
Irrigation frequency $\times$ Soil type	Grid count (turf cover %)			
Daily $\times$ Sand	1.6 b	4.9 b	10.3 b	15.0 b
Daily $\times$ Silt loam	6.9 a	24.5 a	51.5 a	67.4 a
Every 3 days $\times$ Sand	0.0 c	0.0 c	0.0 c	0.0 c
Every 3 days $\times$ Silt loam	1.9 b	3.9 cb	6.9 cb	11.7 b
<i>p values</i>				
Irrigation frequency $\times$ Soil type	0.0026	<.0001	<.0001	<.0001

Note: Means within a column with a common letter or no letters are not significantly different according to Fisher's protected LSD test ($\alpha = .05$). Bolded *p* values indicate significance at $p < 0.05$. Abbreviation: DAP = days after planting

Appendix D - Additional Figures for Chapter 5



Figure D.1. Automated rainout shelter used for field experiments at Rocky Ford.



Figure D.2. Field plot layout and seeding procedure at Rocky Ford. (A) Prepared experimental plots under the automated rainout shelter. (B) Turfgrass seed manually broadcast within each plot.

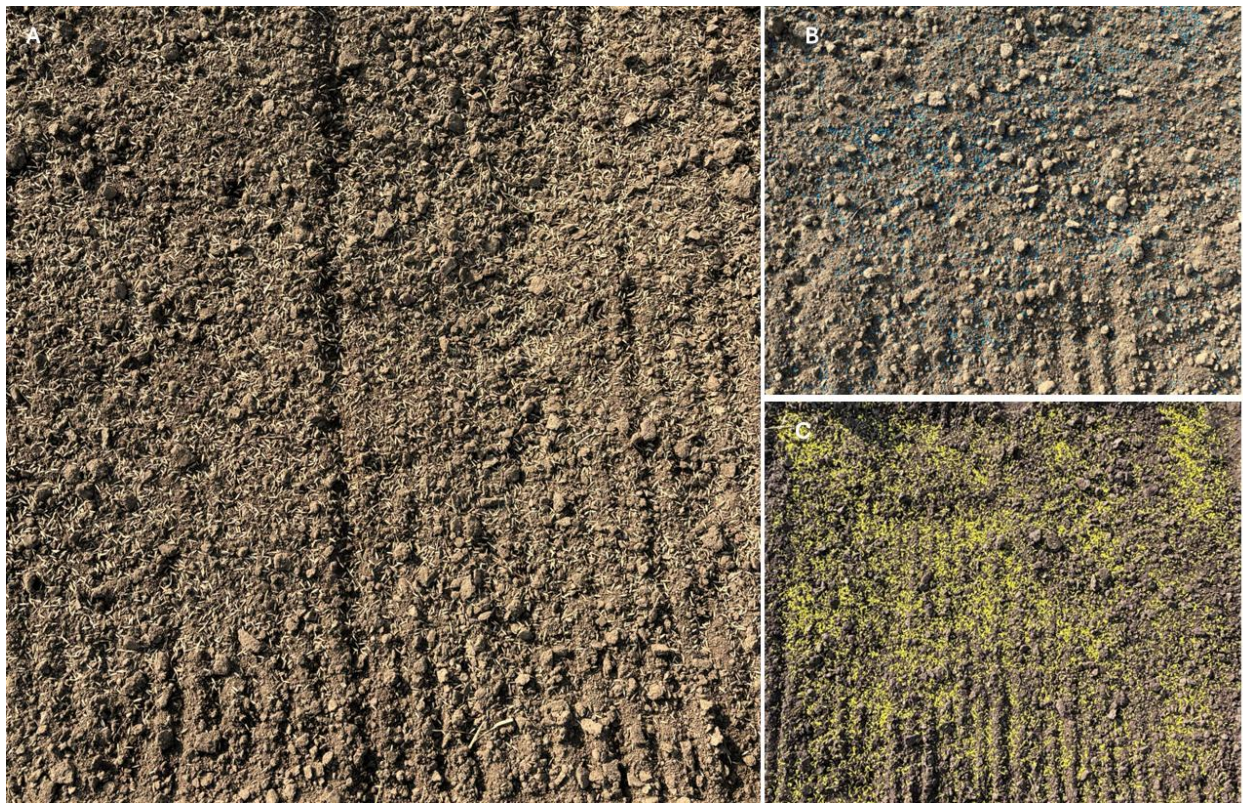


Figure D.3. View of turfgrass seed on the soil surface after seeding. (A) Noncoated tall fescue seed. (B) Coated Kentucky bluegrass seed. (C) Coated tall fescue seed.

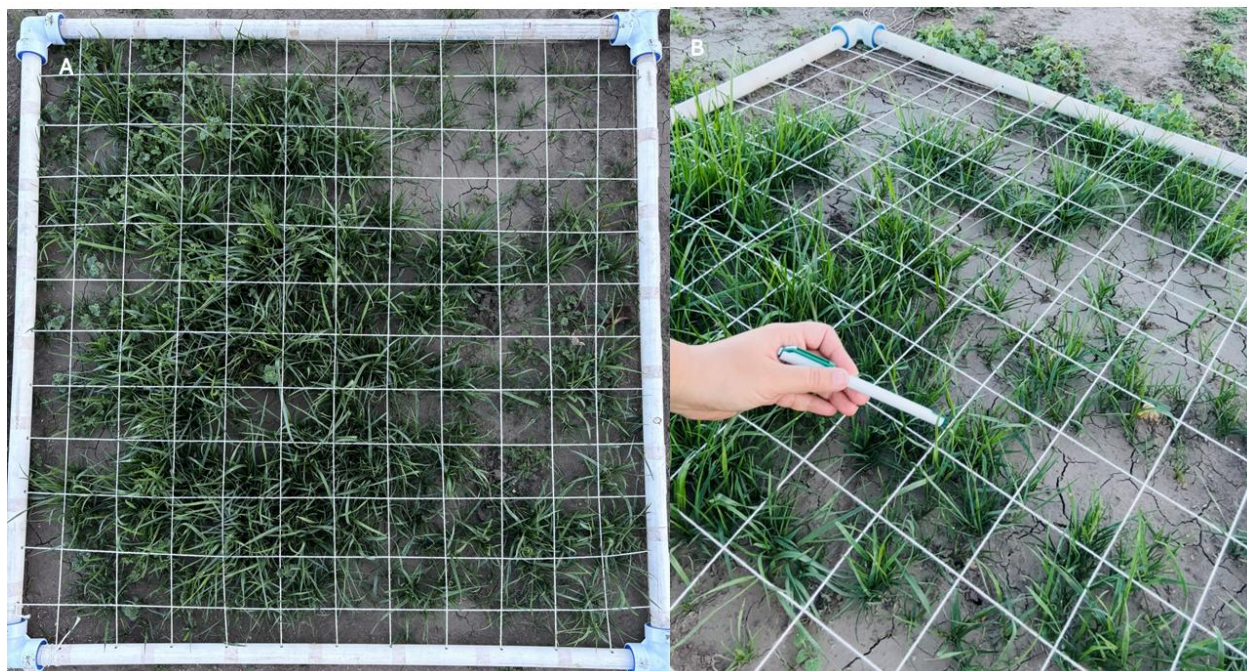


Figure D.4. Turfgrass cover assessment using a grid-count method. (A) Grid frame with 100 intersections placed over an individual field plot. (B) Turfgrass presence recorded at each grid intersection to calculate percent turfgrass cover.